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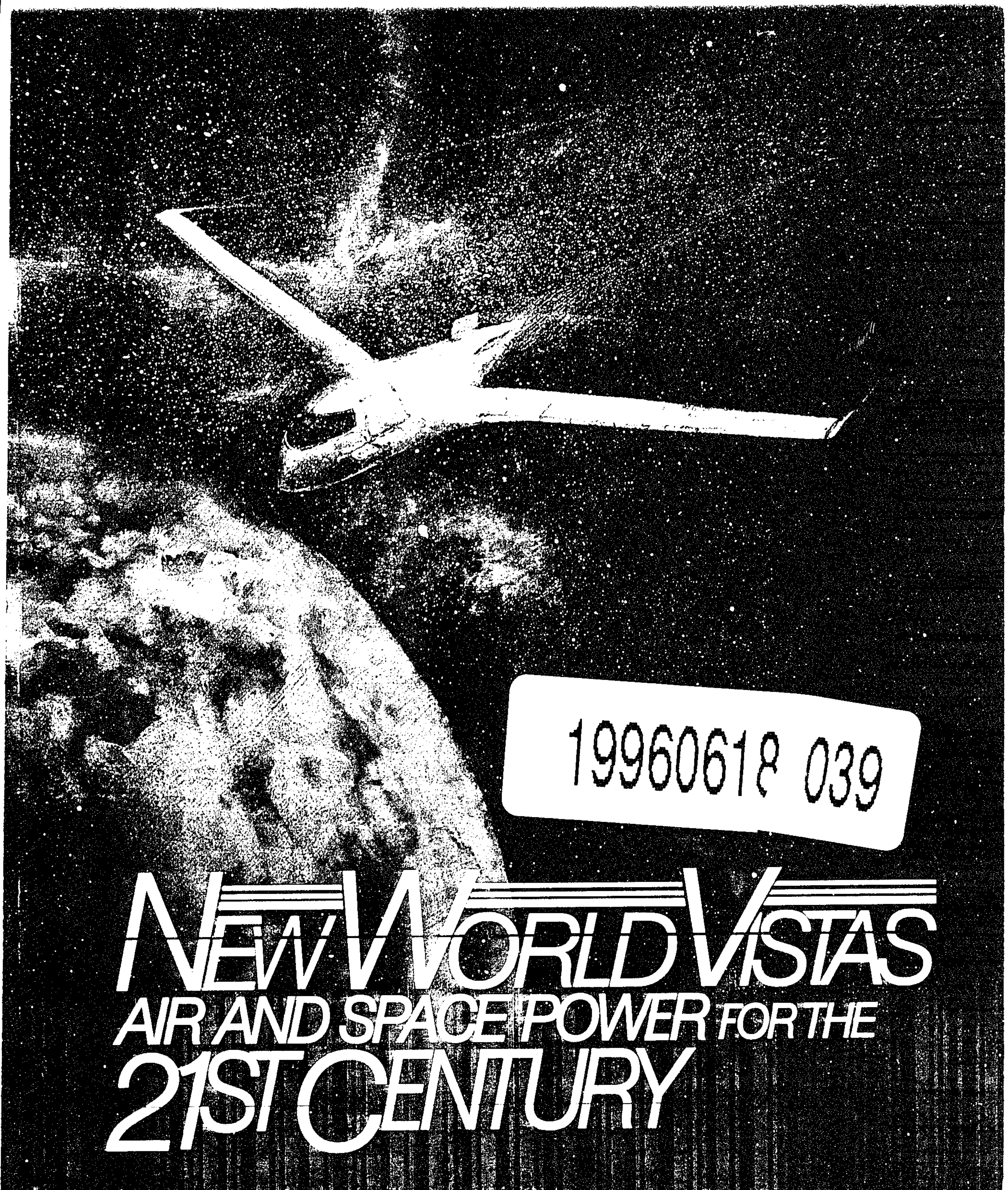
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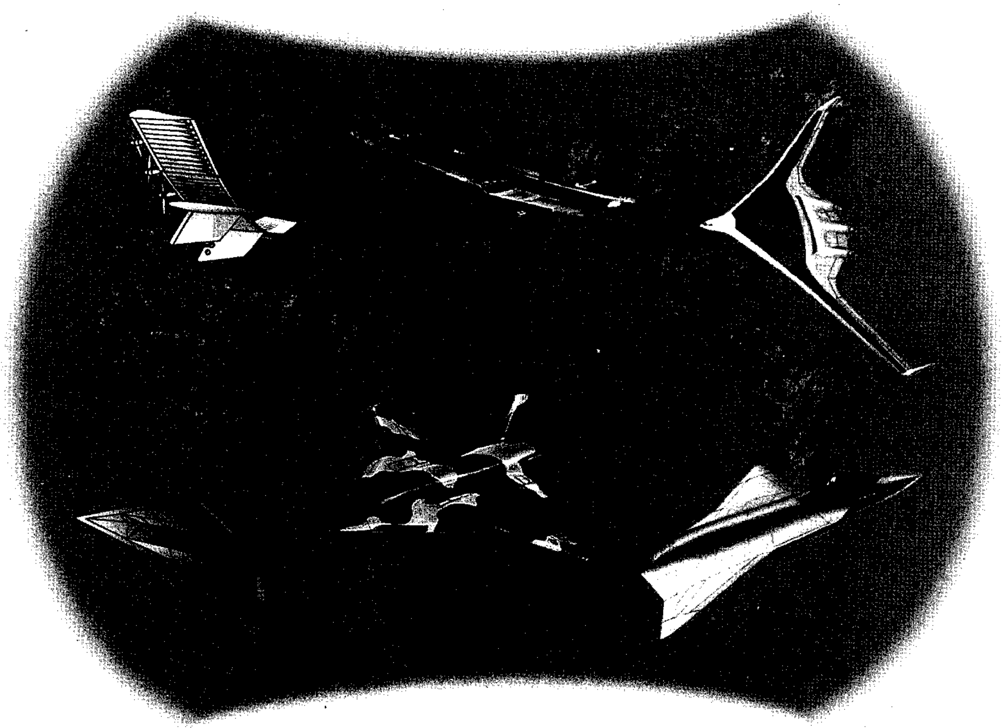
NEW WORLD VISTAS
AIR AND SPACE POWER FOR THE 21ST CENTURY

AIRCRAFT & PROPULSION VOLUME

This report is a forecast of a potential future for the Air Force. This forecast does not necessarily imply future officially sanctioned programs, planning or policy.

New World Vistas 1995



AIRCRAFT and PROPULSION TECHNOLOGIES

Preface

Unquestionably the 1990s have been a time of drastic change for the world and for the Armed Forces of the United States. For over forty years the clearly defined threats of the Cold War have driven the U.S. Air Force to compete for performance superiority across many technological fronts. Today there are no clearly defined forces or enemies that demand response. Furthermore, defense budgets will continue to decrease. The resulting challenge for the Air Force is to be prepared for any threat while handicapped by decreasing defense budgets.

Two overarching factors are acknowledged for the 21st Century. First, the U.S. Air Force must be able to field superior air-vehicle systems to counter any threat that may arise - true even though a future is predicted where information dominance is crucial. Thus, the enabling air-vehicle technologies needed to provide that superiority must be pursued.

Second, in times of budget stress, cost considerations are as important as performance. While system performance is necessary to defeat the enemy, it cannot be considered sufficient unless the capability or the weapon systems are affordable. Thus cost is an essential design parameter for any new air-vehicle system.

It is within the spirit of these factors that this volume has been assembled. A forthright attempt has been made to evaluate the aircraft and propulsion technologies and to project the technological potential for the future.

Richard G. Bradley
Chairman

Executive Summary

Introduction

The Aircraft and Propulsion Panel was assembled to assist the United States Air Force Scientific Advisory Board (SAB) in the New World Vistas Study. Panel members are listed in Appendix B. The panel was chartered to identify and recommend technologies and concepts that will favorably impact the USAF's ability to accomplish its mission in the future. The panel worked closely with the application panels and other technology panels in order to assure that the technology requirements for proposed air vehicle systems were considered. Five panel meetings were held from January through June with technical specialists from Headquarters USAF; Navy, Air Force, and NASA Laboratories; ARPA; AFOSR; ONR; NAVAIR; and JAST. The final volume was assembled during the New World Vistas Summer Study and is summarized in the following paragraphs.

The precision delivery of lethal or non-lethal weapons and the timely dispersion of force around the globe will remain essential parts of a successful campaign. The technologies of warfare are undergoing change and information is a key asset for warfare. While the nature of air vehicles and their propulsion systems may be expected to undergo a transformation more adapted to the needs of future warfare, their fundamental mission remains. Vehicles of the future will allow relatively easy upgrade to take advantage of rapidly advancing technologies in sensors, weapons, and communications. Designs for low cost manufacture and operation will be crucial. Some may be special purpose in design, perhaps for unique weapons or sensors.

In the evolving scenario of modern information rich warfare, air vehicles will retain the need for at least six key attributes: speed, range, lethality, flexibility, survivability, and affordability. Affordability is an attribute that has increased in importance in the post cold war era. Affordability means reduced cost of the weapon system from conception and development through the life of the system. There are seven basic missions for air vehicles that are envisioned to endure: strategic bombing, air mobility, strike, air superiority, recce intel, special operations, and support of space operations, including access to space. Combined, these attributes and missions serve as a basis for identifying specific vehicle concepts and their important technologies in the following discussion.

Air Vehicle Concepts

Large Long-Range Aircraft

Large transonic aircraft of the 1-million-pound class that will have an unrefueled range of 12,000 miles will be possible within the next two decades. Supersonic aircraft in the 500,000-pound class with unrefueled range of 6,000 miles will also be possible in the same time period. Aircraft of these sizes could be designed for air transport or bomber missions. Technology advances in structures, aerodynamics, propulsion, and flight systems will provide the foundation. The opportunity exists for unprecedented partnerships between civil and military sources to develop the technology and a design suitable for both military and civil express freight applications. It appears that the commercial transport market could lead the military use of future-technology large transports. Thus, the military could leverage this marketplace to substantially reduce the development cost for future transonic transports.

Enabling Technologies

Many of the aircraft technologies required are currently being developed by NASA under the Advanced Subsonic Transport Program and High Speed Research Program. Continued development of these technologies in aerodynamics, airframe structure, flight system, and propulsion can lead to significant improvements in transport aircraft. Technologies critical to the development of large transport aircraft are summarized in the following table.

Summary of Critical Technologies for Large Long-Range Aircraft

TECHNOLOGY	EXAMPLES
Integration Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Modeling and Simulation
Aerodynamics Advanced Configurations	High Aspect Ratio/Strut-Braced Wings; Blended Wing/ Body; Multiple Fuselages
Airbreathing Propulsion Very Low TSFC Turbine Engines	High-Temperature Engine Materials and Structures; High Bypass Ratio; High Temperature Lubricants
Structures Adaptive Structures	Smart Materials; Active Load/Thermal Control
Configuration and Concept Design	Tailored Structures; Concurrent Design
Vehicle Control Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW
Human System Interface	External Vision; Displays
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls
Aircraft Subsystems More Electric Aircraft	Light Weight High Power Converter Modules
Energy Storage and Generation	Aircraft Defensive Systems; Light Weight Batteries and Fuel Cells

Uninhabited Aircraft

Uninhabited aircraft are those air vehicles that do not have on-board presence of pilot or aircrew. All control functions that are normally associated with piloting are performed by on-board controllers, and information used by those controllers may be supplied by humans off-board via data links. These vehicles span the range from completely autonomous after launch (like cruise missiles) to complete dependency on humans for some mission and/or flight critical function (remotely piloted vehicles).

Determination of whether a vehicle should be inhabited or not depends upon the functional requirements it must perform in the overall war fighting system. In some cases, human presence on board air vehicles may not be desired due to added cost, size, weight, or low probability of survival in the threat environment. During the design of the overall war fighting system, the design tradeoffs must take into account human mental and physical capabilities, as well as technologies to replicate or enhance those capabilities. Further, bandwidth limits for transmitting data to and from the uninhabited aircraft while protecting communications in a jamming or spoofing environment must be considered.

Uninhabited aircraft provide the potential for significant cost savings at the vehicle level and at the overall war fighting system level because of reduced crew training requirements and the ability to replace highly trained, multi-talented crew members with specialists. Once human presence is removed from air vehicles, unique capabilities can be addressed, such as long-endurance flight and miniaturization of vehicle size. A vehicle can also be flown in a high-threat, low-probability-of-survival environment to deliver weapons to launch points, deliver cargo, or perform high-risk development flight testing without placing pilots at risk. The air vehicle system and structure can be designed for extremely high maneuver loads and agility since there are no crew constrained g-limits. Further, new approaches to launch and recovery can be pursued. For example, from and to ground vehicles, aircraft carrier ships, airborne vehicles, suborbital vehicles, and satellites.

Enabling Technologies

The design and development of an uninhabited aircraft depends upon most of the tools and data bases needed for inhabited vehicles, except that new tools and technologies are needed for those aircraft that are meant to fly beyond current vehicle operational envelopes, that is, very high altitude vehicles, very small miniaturized air vehicles, or very high dynamic pressure cruise and/or maneuver vehicles. Technologies critical to the development of uninhabited vehicles are summarized in the following table.

Summary of Critical Technologies for Uninhabited Vehicles

TECHNOLOGY	EXAMPLES
Integration Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Design of Ultra-small Vehicles; Modeling and Simulation
Test and Evaluation	Integrated Test, Simulation, and Computational Analysis with Off-Board Systems, and Controllers
Vehicle Control Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW
Human System Interface	Integration with Off-Board Controllers and Cognitive Engineering
Multivariable Design Tools and Criteria	Multivariable Active Control; Control Laws for Expanded-Envelope Flight
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls

Special Operations Aircraft

It is envisioned that the requirements for special operations will dramatically increase in the future. The need for flexible covert intervention in both developed and underdeveloped nations around the world appears certain. There is a need for a new affordable, reliable, survivable, special operations forces (SOF) vehicle that has a range of 1500 nautical miles, high subsonic flight speeds, and capability for VTOL/hover at the point of insertion and/or extraction, and low acoustic, visual, IR, and RF signatures. The payload for this vehicle would include a limited number of troops, a small personnel carrier, weapons, sensors, transmitters, and so forth. Although a vehicle with all of these characteristics cannot be produced with the technology available now, foreseeable improvements can make it possible to field much of the capability within 5 to 10 years and a fully capable aircraft within 20 years.

Enabling Technologies

The key enabling technologies include planned airbreathing propulsion system improvements, signature reduction, materials and structural technologies, and the development of vertical lift schemes to include fan and advanced configuration technology. Technologies critical to the development of special operations aircraft are summarized in the following table.

Summary of Critical Technologies for Special Operations Aircraft

TECHNOLOGY	EXAMPLES
Integration	
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability
Aerodynamics Advanced Configurations	High Aspect Ratio/Strut-Braced Wings; Blended Wing/ Body; Multiple Fuselages
Airbreathing Propulsion High Thrust-to-Weight Turbine Engines	Variable Cycle Engine; Low Observables
Powered Lift	Vectored Thrust; Lift Fans; Nozzles
Structures Advanced Airframe Materials	Lightweight Materials; Survivability; Low Observables
High-Temperature Airframe Materials	Exhaust Impingement
Configuration and Concept Design	Tailored Structures
Vehicle Control Integrated Control System Architecture	Autonomous Active Control; FBL/PBW
Human System Interface	External Vision; Displays
Fault Diagnostics and In-Flight Reconfiguration	Health and Condition Monitoring; In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls
Aircraft Subsystems More Electric Aircraft	Integrated Aircraft Subsystems; Reliability; Survivability

Long-Endurance Aircraft

Multiple missions have been identified for uninhabited aircraft that can fly for very long periods of time (days to weeks or months) at ultra- high altitudes, i.e. above 80,000 feet. These missions include reconnaissance and environmental monitoring, communications, and weapons platforms. Low subsonic speeds are acceptable. The enabling technologies for development of successful very long-endurance aircraft are beginning to appear. The technology discussion will center on a mission requirement for ultra high altitude above 80,000 feet, low subsonic speeds, indefinite endurance, and a 2,000 pound payload.

Enabling Technologies

Key technologies for accomplishment of the very long-endurance aircraft mission include high strength materials, active control of a very flexible structure, low drag aerodynamic

design, and propulsion system advances. At altitudes above 80,000 feet, electric motor driven propellers are attractive with solar cell power source and batteries for storage. Technologies critical to the development of long-endurance aircraft are summarized in the following table.

Summary of Critical Technologies for Long-Endurance Aircraft

TECHNOLOGY	EXAMPLES
Integration Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Modeling and Simulation
Aerodynamics Advanced Configurations	High Aspect Ratio/Strut-Braced Wings; Blended Wing/Body; Low Observables; Hypersonic L/D; High q/Low Altitude
Solar Propulsion HALE Propulsion System	Electrical Motor or Turboboost Reciprocating Engine
Structures Advanced Airframe Materials	Advanced Composites; Advanced Lightweight Materials
Configuration and Concept Design	Tailored Structures; Concurrent Design
Vehicle Control Integrated Control System Architecture	Autonomous Active Control of Flight and Avionics; FBL/PBW
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls
Aircraft Subsystems Heat Load Management	Solar Cell Cooling; Avionics Cooling; Reduced IR Signature
Energy Storage and Generation	Batteries; Solar Cells; Fuel Cells; Flywheels

Modular Vehicles

The concept of modularity in vehicle design and operation can provide mission flexibility and extend the useful life of a vehicle system through upgrades and improvements. Three levels of modularity are envisioned: manufacturing level, depot level, and flight line level. The levels are applied within a given class of vehicles. At the manufacturing level, the aircraft and the manufacturing processes are designed to tailor aircraft fabrication and assembly so that modules may be permanently built-in on the production line. For example, a carrier-capable landing gear module and fuselage keel structure could be built-in for Navy aircraft. At the depot level of modularity, one could find, for example, replacement of a fuel tank module with a lift fan module or replacement of a landing gear suitable for safe 10,000 foot runway operation or one suited for unprepared runway operation. At the flight line level of modularity, one would find provisions to install mission unique avionics, weapons, external pods, and so forth. The modular vehicle concept represents an extension of the avionics common module concept to a full-up air vehicle system.

The objective of the modular concept is to build in flexibility for the system while, at the same time, to lower the overall life cycle cost. The concept applies to all classes of air vehicles: fighters, transports, special purpose vehicles, and so forth, and can be made compatible with US Army and Navy applications. The benefits are obtained by

- tailoring aircraft capabilities using modules for specific mission needs,
- designing-in convenient fault isolation and access to modules to reduce mean-time to remove and replace them,
- accommodating a flow of product improvement upgrade modules for avionics, displays, subsystems, weapons, engines, and selected structural components, and
- putting in place the logistics infrastructure to handle modules which are common across many weapon systems and can be shipped overnight to provide just-in-time mission capability.

Enabling Technologies

The modular concept requires improved "design-to" tools that include the features of design-to-cost and definitions of standard interfaces so that modules can be specified for form, fit, and functionality. Structural load sharing concepts are important as well as control laws and criteria. Also important are advancement in the disciplines of design and manufacture (using modularity-capable tools and standards), support and logistic system design, and training and pre-mission activities. Some of these technologies are being examined in the JAST program. Continued development should pay large dividends in the introduction of modularity in air vehicle systems. Technologies critical to the development of modular vehicles are summarized in the following table.

Summary of Critical Technologies for Modular Vehicles

TECHNOLOGY	EXAMPLES
Integration Design Tools for Affordability	Detailed Cost Models: Vehicle, Module Manufacturing Process, Training (with Module Configurations), and Logistics Support of Modules
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability with Modules; Multidisciplinary Design Optimization; Module Production; Modeling and Simulation (to include Cost)
Aerodynamics Advanced Configurations	Low Observables; Design of Modular Wings, Tails, and Fuselage Sections
Airbreathing Propulsion High Thrust-to-Weight Turbine Engines	Variable Cycle Engine; Design of Inlet and Nozzle Modules
Structures Configuration and Concept Design	Tailored Structures; Concurrent Design; Load-Sharing by Modules
Vehicle Control Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW
Human System Interface	Field-of-View Sensors; Display Presentation Formats; Integration with Off-Board Controllers; Cockpit Modules
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft/Health Monitoring and Diagnostics; Automated Reconfigurable Controls to Account for Module Configuration
Aircraft Subsystems More Electric Aircraft	Modular Light Weight/High Power Subsystem Components
Thermal Management	Avionics, Cockpit, Sensors, Weapons, Skin, and Engine Thermal Management Modules
Ground Operations	System Change-out; Module Handling

Hypersonic Vehicles

Sustained hypersonic flight offers revolutionary improvements in future warfighting and space launch capabilities. Hypersonic speeds greatly enhance survivability by practically eliminating enemy defensive capabilities and greater lethality through the kill potential offered by ultra high kinetic energy impact. Some attractive concepts are listed below.

Missiles

Within the next 10 years hypersonic missiles can be developed that can accelerate to Mach numbers of 6 to 8 and cruise for several hundred (700-800) miles to a target within 10 to 15 minutes from launch. Ground impact velocities of Mach 4 to 5 are achievable if the missile is powered in the terminal phase of flight.

Maneuvering Reentry Vehicle

At the higher end of the Mach/altitude spectrum is a hypersonic maneuvering reentry vehicle, a missile that is boosted to Mach 15 to 20 with a ICBM/IRBM, separated at 150,000 foot altitude, and glides to the target with a large area footprint (3,000 miles cross range and 10,000 miles down range). There is no propulsion system on the missile and Mach 4 to 6 impact velocity can be achieved to penetrate deeply buried targets.

Rapid Response Global Reach Aircraft System

By about 2010-2020, the technology can be developed for a global transatmospheric aircraft that flies up to Mach 16 to 18 on airbreathing propulsion to reach any point on Earth, and return to a CONUS base in less than 2 hours. Global reach aircraft can also be designed with lower Mach number capability and less-than-total- global range, for example Mach 8 to 12 with 10,000 mile range or Mach 6 to 8 with 8,000 mile range. In this flight regime, airbreathing propulsion (ramjet/scramjet) offers a three-to-one advantage in fuel specific impulse over an all-rocket engine. Below Mach 8, endothermic hydrocarbon-based fuels will provide sufficient cooling and thrust. The higher density of the hydrocarbon fuels compared to hydrogen results in a smaller and possibly cheaper aircraft. The coupling of aero-thermal-elastic effects with the problems of controlling the aircraft impose constraints on the flight management system.

Space Launch Support

The global transatmospheric hypersonic aircraft described above could also be the basis of a reusable launch vehicle system to deliver payloads to orbit on short notice with the flexibility of orbital inclination, orbital altitude, and with reentry from any low earth orbit in one revolution to return to its CONUS base. Several options are possible for the hypersonic RLV system to support Air Force needs for on-demand, all azimuth, low cost launch of medium mass (up to 25,000 pounds) payloads to LEO.

Enabling Technologies

A wide spectrum of technologies will be required to enable the development of the hypersonic vehicles for the above missions. Technologies critical to the development of hypersonic vehicles are summarized in the following table.

Summary of Critical Technologies for Hypersonic Vehicles

TECHNOLOGY	EXAMPLES
Integration Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Modeling and Simulation
Aerodynamics Advanced Configurations	Waveriders; Hypersonic L/D
Flow Control	Transition Control
Design Methods	Wind Tunnel Test Techniques; CFD
Facilities	Hypersonic Aero Facilities
Airbreathing Propulsion Combined Cycle Engines	
Dual-Mode Ramjet/ Scramjet	
Facilities	Realistic Test Conditions
Structures Advanced Airframe Materials	Metallics; Advanced Composites; Advanced Light weight Materials
High-Temperature Airframe Materials	Hypersonic Airframes; Exhaust Impingement Struc tures
Adaptive Structures	Smart Materials; Active Load/Thermal Control
Configuration and Concept Design	Tailored Structures; Concurrent Design
Facilities	
Vehicle Control Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/ PBW
Multivariable Design Tools and Criteria	Multivariable Active Control; Cognitive Engineering-Based Criteria; Control Laws for Expanded-Envelope Flight
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft/Health Monitoring and Diagnostics; Automated Reconfigurable Controls
Aircraft Subsystems Heat Load Management	Component Life
Endothermic Fuels	
Ground Operations	Takeoff and Landing Systems

Future Attack Aircraft

By approximately 2025, a new type of low-cost, small, attack aircraft will be able to deliver ten 500-pound brilliant low-signature weapons to surface or subsurface targets. This aircraft would replace the F-117 and F-16 aircraft. Multiple roles such as defensive counter-air, ground-target attack, BDA, recce, or even limited special operations can be accomplished. The aircraft will be a small aircraft weighing less than 20,000 pounds including weapons, because it will either operate close to the targets or be deployed from large transport aircraft. The cost of the aircraft would be further minimized by the small size of the aircraft, modular design, smart aircraft components, system level integration of technologies and transfer of avionics functions to systems off-board the aircraft.

Through the integration of high powered laser and microwave defensive weapons, the aircraft will be invulnerable to attacking surface-air and air-air missiles at distances of 1-3 kilometers from the aircraft. Complete spherical coverage around the aircraft can be defended by very rapid agile maneuvers by the aircraft to provide line-of-sight aiming of the laser microwave weapon. This defensive shield removes the surface-to-air, air-to-air threat so that the attack aircraft can deliver its air-to-ground weapons.

Enabling Technologies

The key enabling technology is a laser and microwave defensive shield operating out to 1-3 kilometers radius from the airplane in any weather condition. The conformal laser arrays would be able to defend against missiles during clear weather. Conformal microwave antenna arrays would be able to defend against missiles during inclement weather or through obscurants. The volume and weight of the defensive shield is projected to be a few cubic feet and a few hundred pounds. One-to-two megawatts of electrical energy is available directly from the aircraft engine shaft which could allow continuous operation of the laser and microwave system.

Air vehicle technologies critical to the development of future attack aircraft are summarized in the following table.

Summary of Critical Technologies for Future Attack Aircraft

TECHNOLOGY	EXAMPLES
Integration Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Design of Ultra-small Vehicles; Modeling and Simulation
Airbreathing Propulsion High Thrust-to-Weight Turbine Engines	High-Temperature Engine Materials and Structures; Variable Cycle Engine; High Temperature Lubricants; Integral Starter-Generator
Structures Advanced Airframe Materials	Metallics; Advanced Composites; Advanced Light weight Materials
Configuration and Concept Design	Tailored Structures; Concurrent Design
Vehicle Control Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW
Human System Interface	External Vision; Displays; Integration with Off-Board Controllers; Laser Eye Protection
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft/Health Monitoring and Diagnostics; Automated Reconfigurable Controls
Aircraft Subsystems More Electric Aircraft	Power Management for Active Defensive Systems; Energy Storage and Generation
Heat Load Management	Component Life; Reduced IR Signature; Thermal Management of Heat From Laser or Microwave Weapon; Endothermic Fuels
Crew Escape	Aircrew safety/effectiveness

Air Force Laboratory Infrastructure Issues

In general, the Air Force is properly organized to address the aircraft and propulsion technologies that support the concepts identified by the New World Vistas Aircraft and Propulsion Panel. The primary Air Force organizations are the Flight Dynamics Directorate, Aeropropulsion and Power Directorate, and Materials Directorate of Wright Laboratory. These directorates are connected through technical associations and in some cases formal agreements with other relevant AF, Navy, NASA, and DOD organizations. Since the Air Force contracts out approximately 80% of its science and technology program, Wright Lab is well connected to industry and academia.

Nevertheless, closer coordination of all the government, industry, and university community involved with aircraft and propulsion technologies could further strengthen the DOD military aeronautics program in an environment of uncertain budgets and personnel downsizing in all three of the above sectors. There are several mechanisms in place for technical coordination such as DOD Project Reliance, DOD Technical Area Plan/Technology Development Approach Activity, etc., and the recent (July 95) initiative to identify increased collaboration between Air Force and NASA. These mechanisms are working well to coordinate on-going programs, but more emphasis is needed on joint up-front planning of programs.

Some specific issues that need further effort to determine their resolution:

- The growing importance of S&T as the number of development programs diminish requires that AFMC/ST and SAF/AQT be combined into one organization reporting directly to SECAF. This office would be the Assistant Secretary of the Air Force for Science and Technology, on a level equivalent to the Assistant Secretary for Acquisition (SAF/AQ). Success of this office should be judged by transition of technology from S&T to acquisition. The four Air Force labs would report directly to this new office, which would have responsibility for all Air Force S&T resources, including laboratory personnel.

- Coordination and inter-dependency between Air Force and NASA needs to be institutionalized in a more formal technology coordinating panel between DOD (Air Force-lead for fixed wing aircraft) and the four NASA aeronautics centers (Ames, Dryden, Langley, and Lewis) each of which is essential to Air Force aeronautics technology development.

- The Air Force needs to strengthen joint technology planning and program execution with Navy, Army, ARPA, Department of Energy National Labs and other governmental entities developing air vehicle and propulsion/power technologies.

- Air Force labs need to increase the interaction with industry and academia through open facility use, personnel exchanges, and joint collaborative projects.

- The AFOSR 6.1 basic research program should be jointly planned and managed with the laboratory 6.2/6.3 program. There should be an ongoing personnel exchange between AFOSR and the Air Force labs.

- The high cost of AEDC and AFFTC testing precludes the Air Force laboratories from testing as much as needed to develop the technologies identified by New World Vistas.
- The Air Force needs a well thought-out plan for facility modernization to support New World Vistas technologies and concepts. The Air Force should commit the necessary resources to implement the plan.
- Wright Lab needs to manage its downsizing plan carefully (30% reduction by 1999 from 1993 levels) in order to support the technologies and system concept evaluations outlined in the New World Vistas report. Further downsizing would greatly jeopardize the role of the Laboratory to manage and execute the programs that support the New World Vistas recommendations. The government must retain its technical expertise in order to orchestrate the Air Force S&T program.
- The DOD Laboratory Quality Improvement Program (LQIP), being formulated by AFMC/ST, should be implemented as soon as possible.
- The aircraft and propulsion technology S&T program is approximately 20% to 25% of the Air Force total S&T budget. This percentage should not decrease, in order to further the recommendations of the New World Vistas Aircraft and Propulsion Panel.

Conclusions and Recommendations

This panel envisions that the Air Force will

- *be more reliable, flexible, survivable, and affordable,*
- *provide global reach and project global power independent of in-flight refueling and air base infrastructure outside the CONUS,*
- *exploit uninhabited vehicles and modularity to increase operational capability and flexibility and reduce cost,*
- *extend capabilities in special operations, airborne reconnaissance, and humanitarian relief,*
- *expand the air vehicle flight regime to orbital velocities and to altitudes at the edge of the atmosphere, and*
- *integrate air vehicles into information-dominated warfare.*

Based on this vision, the following conclusions and recommendations are made:

The projection of power, whether regional or global, will be critically important to the Air Force for the foreseeable future. This power projection is dependent upon the quality of the USAF's air vehicle systems. Thus, investment in air vehicle technologies is critical for the continued superiority of the USAF. Technology development is especially important at the present time when new weapon system starts are not planned for a long period of time.

- **Recommend a continued strong investment in air vehicle technologies.**

Significant advances in warfighting capability have been identified through seven revolutionary system concepts. These include large long-range aircraft, uninhabited aircraft, special operations aircraft, long-endurance aircraft, modular vehicles, hypersonic vehicles and future attack aircraft. Critical technologies necessary to support these concepts are not yet mature.

- **Recommend vigorous pursuit of the enabling technologies for these revolutionary air vehicle concepts.**

Affordability will dominate development, procurement, and operation of future weapon systems. Cost prediction is essential to the determination of affordability. The prediction of cost determination based upon rational measures of merit is a fruitful area for research. Successful introduction of new technologies requires a close coupling between cost and system capability.

- **Recommend that a research effort be established to define fundamental principles of cost determination.**

- **Recommend that all S&T projects consider the proper balance between life cycle cost and capability.**

The post cold war slowdown in the development of new air vehicle systems raises a serious concern for retention of the Nation's design capability. Further, efforts to improve the performance, capability, and/or affordability of air vehicles require innovative approaches to reduce design cycle time and simplify manufacturing processes. All can be validated only by developing and producing hardware for test and evaluation. One effective way to retain and improve the Nation's design capability is through experimental and/or prototype aircraft programs.

- **Recommend that the Air Force pursue an active experimental aircraft and flight research program.**

Much of the US aeronautics test facility base is over 40 years old, almost twice its design lifetime, and generally inadequate to provide the design information and risk reduction needed in future air vehicle development programs. Some of the facility deficiencies can be overcome with facility improvement and modernization programs. However, much of the facility base can best be updated by facility replacement, where new and highly productive facilities both provide improved test capabilities and permit closure of obsolete facilities. The facility base is grossly inadequate to develop hypersonic air vehicles, and new test facilities are required.

- **Recommend that the Air Force take timely action to define and implement a program for modernization of old facilities and construction of new test facilities that ensures the adequacy of national test facilities to support future military air vehicles.**

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1.0 Introduction

1.1 Future Warfare

Technologies supporting warfare seem to be undergoing a revolutionary change. Some perceive the most vital asset for modern warfare is information. Nevertheless, information is a necessary, but not sufficient condition for victory. The timely dispersion of force around the globe and precision delivery of lethal or non-lethal weapons will remain an essential contributor to the final victory.

The "system-of-systems" concept of warfare contains the requirement for air vehicles to enter into combat[1]. While the nature of vehicles and their propulsion system may undergo a transformation to adapt them to the perceived needs of warfare of the future, their fundamental mission remains and the need for new and advanced vehicles will not disappear. Vehicles of the future may either be designed for a single special purpose or be designed with sufficient flexibility to meet a variety of missions. Whether they will be designed for unique weapons or sensors, or capable of rapid incorporation of different or new technologies, low cost manufacture and operation will be common features.

1.2 Important Attributes

In the evolving scenario of modern, information-rich warfare, vehicles must be based upon six key attributes. These six attributes are noted below in relationship to their contribution to the overall effectiveness in meeting mission objectives.

AFFORDABILITY means reduced cost of the weapon or weapon system from conception and development through the life of the system(life cycle cost).

SURVIVABILITY provides the ability to operate successfully in high threat environments.

SPEED enables the system to respond rapidly to a military need and enhances survivability.

RANGE provides the ability to reach trouble spots anywhere on the battlefield or on the globe with minimal support from tankers or bases.

LETHALITY enables the system to deliver weapons of destruction efficiently and to kill on the first try.

FLEXIBILITY is the ability to accomplish a variety of missions or carry a variety of payloads to meet differing requirements.

The term "affordability" is one that will appear in many places in this report. Affordability is used in many broader discussions of weapon system development, procurement, and operations. However, "affordability" as a concept involves trade-offs against a number of external factors as well as direct cost, cost of development, cost of procurement, and operational and

1. It has been said the current generation of platforms (B-2, F-22, etc.) may be the last. Such a conclusion is not to be supported by even the most ardent enthusiasm for the information age.

maintenance costs. The panel report is narrowly focused on cost. Many of the factors associated with "affordability" are quite beyond the knowledge and control of the aircraft system designer. Thus, the primary concerns in this report associated with "affordability" are the cost parameters, including all those listed above. Cost (and control of costs) is so important it warrants a number of specific remarks.

Historically, costs associated with development, procurement, and operations and maintenance are determined after the fact on the basis of a regression analysis. The independent variables include several measures of system performance, the expected number of weapon systems to be purchased, and perhaps the duration of the development and procurement rate. The resulting regression is often termed a "cost model." The estimates provided by this model are often inaccurate.

There is an increasing body of evidence that cost is related to complexity, often represented by the parts count, and acceptable level of variation in key dimensions. Further, there is an increasing body of evidence that if a cost data base is included as a part of the designer's more general data base, the designer will tend to create a low cost product.

The primary conclusion to be drawn is that the underlying principles of cost determination are not yet fully defined and that cost estimation in this sense is an immature technical discipline. Because of the important part "cost" plays in "affordability," one of the major recommendations of this study will be to invest more resources in this immature technology — cost determination.

1.3 Key Missions

In the evolving information dominated battle scenarios of the future, there are seven basic classes of missions for air vehicles that are envisioned to remain. These missions will serve as a basis for identifying specific vehicle concepts and their important technologies throughout the remainder of the volume.

AIR MOBILITY - Air mobility implies delivering large quantities of troops or material to various locations over the globe and is envisioned to remain a priority for many years to come. Flexibility in payload and unrefueled range are the key requirements.

STRIKE - Strike implies delivering ordnance from air to surface with precision and desired lethality. Fast response to a remote location on the earth may be a prime requirement for precision strike missions of the future. Thus speed, range, lethality, survivability, and operation from crude air bases become very important attributes.

AIR SUPERIORITY - Air superiority is the removal of any threatening vehicle from the air space above the battlefield or the protected territory. The weapon system for air superiority will require flexibility, and its ability to take on the threat may rely on speed, lethality, and survivability.

LONG RANGE BOMBING - Strategic bombing implies delivering ordnance at very long range without the need for tanker support. This mission includes attack on targets to destroy the enemy's will and ability to wage war.

RECCE INTEL - Intelligence information may be gathered in the future with exotic remote sensors in space or at some global location. Even so, a need is envisioned for special air vehicles, either inhabited or uninhabited, to gather intelligence, to provide battle damage assessment, and provide data assimilation and relay for command and control. Range, survivability, endurance, and perhaps speed are important attributes.

SPECIAL OPERATIONS - Special operations requirements will exist well into the future to conduct covert operations, deliver and pick up troops, sensors, and special equipment any place on the earth. Requirements include survivability, range, short and rough field take-off and landing capability, and the ability to operate covertly in all scenarios.

ACCESS TO SPACE/SPACE OPERATIONS SUPPORT - The Air Force's ability to access space on demand may require special airbreathing, reusable vehicles to launch objects to space. Such a vehicle would require, of course, speed to achieve high velocities and could serve as a dual-purpose high-speed strike or recce vehicle.

Affordability is an underlying attribute for all of the systems required to satisfy the missions. Within a key mission category, the absolute values of the attributes may vary significantly from system to system. As an example, for a strike mission the weapon system could be a long range hypersonic strike vehicle in which speed becomes extremely important. On the other hand, a strike vehicle may have medium range stealthy penetration for which speed is not an important attribute.

The following sections of this volume explore some specific vehicle and system concepts (Section 2) for consideration. These concepts form a set which can fulfill all key missions and which span a broad range of important attributes. The concepts are then related to the technology advances (Section 3) that are important for their successful development and production which, in turn, lead to specific recommendations on technologies to be pursued. Following that is a discussion of a number of infrastructure issues (Section 4) that are of importance to the Air Force.

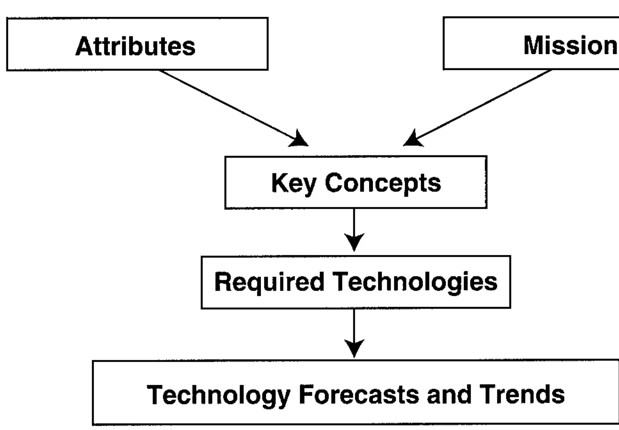


Figure 1.3.1 Process for Defining Technologies

2.0 Air Vehicle Concepts

Within the mission scenario of the future, seven air vehicle concepts will be discussed in detail in this section. They are shown in Table 2.0.1 where the concept and attributes are displayed.

Table 2.0.1 Air Vehicle Concepts for the Future

AIR VEHICLE CONCEPTS	ATTRIBUTES					
	Affordability	Survivability	Speed	Range	Lethality	Flexibility
Large Long-Range Aircraft	H	H	M	H	D	H
Uninhabited Aircraft	H	D	D	D	D	H
Special Operations	H	H	M	H	L	H
Long-Endurance Aircraft	H	M	L	H	L	M
Modular Vehicle	H	D	D	D	D	H
Hypersonic Vehicle	H	H	H	H	H	M
Future Attack Aircraft	H	H	M	M	H	H

H = High M = Medium L = Low D = Mission Dependent

2.1 Large, Long-Range Aircraft

2.1.1 Introduction

Large, long-range aircraft can serve two missions in the future Air Force, air transport[2] and bombing. Many of the technologies required to develop these two vehicles are similar while they differ mainly in their requirement for stealth.

Large transport aircraft such as the C-5 and the C-17 form the backbone of the air mobility fleet today, and are expected to continue to do so well into the future. Large, jet transport aircraft have improved incrementally since their introduction in the early 1950's with the introduction of the KC-135. This forty year incremental advancement could be expected to have exhausted the possibilities for substantial improvements in the performance of these aircraft. This perspective is true for aircraft based on the late 1960's technology suite of turbofan engines, aluminum primary airframe structure, and conventional aerodynamic configurations. On the other hand, during this same forty year period these aircraft have grown substantially in size, with the C-5, C-17, and B747 representing the largest aircraft of this category. The C-5 and

2. Mobility Applications Panel Report, Section 4.1, 4.2.

B747, the largest of these aircraft, were developed in the 1960's. There is current commercial interest developing in an aircraft roughly 1.5 to 2 times the size of the B747 and it appears there are no technological barriers to its development. The only major difficulties in commercial introduction of such large aircraft appear to be operational (e.g., gate accommodation, runway loading, etc.). Thus, based on conventional technologies, the possibilities for future large transport aircraft appear to be in substantial increases in size (and hence payload) with little, if any, expansion of the performance envelope.

During this same forty year period there have been significant technological developments which, if applied to large transport aircraft, could dramatically expand the performance envelope. These advancements can extend the unrefueled range and increase the speed of these aircraft and potentially reduce the field length requirement. This discussion will focus on the attributes of improved range and affordability along with substantial increases in payload and size. The possibility of a very high speed transport will also be touched upon. The attributes of flexibility and survivability will also be considered.

Long-range bombers, in contrast to transports, have recently undergone a major change in technology. The B-2 represents a major departure from the technology incorporated in the B-52 and B-1, driven mainly by the requirement for stealth. Modern controls technology allows the elimination of the vertical tail and the flying-wing configuration. Future bombers' major requirements for performance gains are increased range (allowing for CONUS-based, global strike) and increased speed (allowing for very rapid reaction in the initial stages of conflict).

2.1.2 Performance Potential

Performance potential will be considered in three separate categories: transonic transports (aircraft with essentially the same speed as today's large transport aircraft), transonic, long-range bombers, and large, long-range supersonic transports or bombers. It is recognized that the supersonic transport and bomber will be different aircraft, but they have similar technology suites.

Technologies to support these levels of performance could be well in hand by 2010 and commercial aircraft having substantial fractions of this performance potential could be com

Table 2.1.1 Defining Parameters for Transport Aircraft

Performance Parameter	Transonic Transport	Transonic Long-Range Bomber	Supersonic Transport/Bomber
Range or Combat Radius	12,000 NM.	8,000 NM	6,000 NM
Speed	0.8 Mach	0.8 Mach	2.4 Mach
Payload	0.1 - 0.5 M pounds	0.1 - 0.5M pounds	0.05 - 0.1M pounds
Field	short	10,000 ft.	10,000 ft.

mercially operational by that time. Thus, it appears that the commercial transport market could lead the military use of future technology large transports, or the military could leverage this marketplace to substantially reduce development costs for future transports.

2.1.3 Performance Technology Options

Aerodynamics

Transonic large, jet transport aircraft have had approximately the same lift-to-drag ratio (L/D) since the introduction of the KC-135. The 1950's technology L/D of about 17 has slowly crept up to about an L/D of 20 in 1990's technology aircraft. Technologies which could lead to L/D of over 40 are known and some have been demonstrated in flight test. These technologies include viscous drag reduction technologies such as laminar flow control and riblets. Advanced configuration options include very-high-aspect-ratio strut-braced wings (Figure 2.1.1), dual fuselages, blended wing/bodies (Figure 2.1.2), and joined wings. The viscous drag reduction and configuration options can be combined to provide additive benefits to achieve the most extreme values of L/D. Configurations developed for long-range bombers must incorporate stealth requirements.

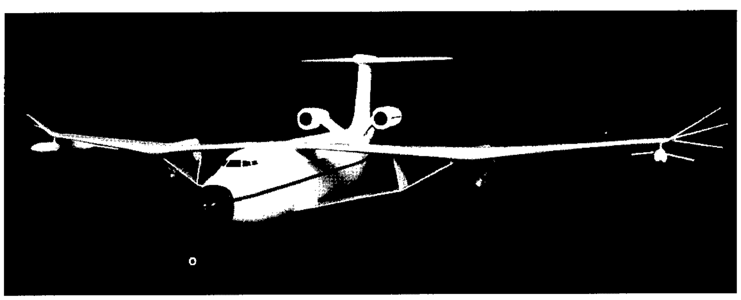


Figure 2.1.1 Very-High-Aspect-Ratio, Strut-Braced Wing, Global-Range Transport Concept

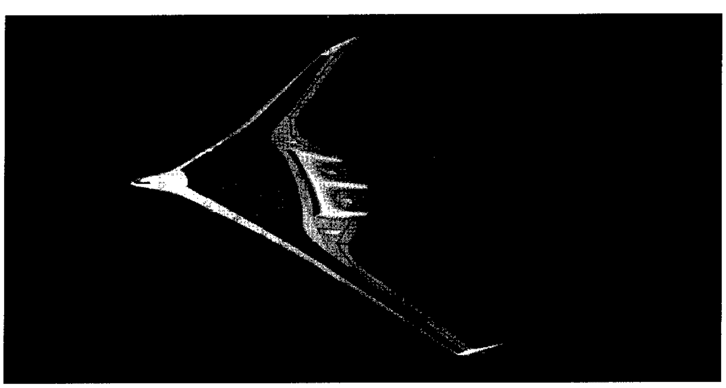


Figure 2.1.2 Blended Wing-Body Transport Concept

Other aerodynamic technologies can be used to improve take-off and landing performance of these aircraft. Conventional high-lift system performance can be improved through viscous flow control technologies such as micro vortex generators, which have demonstrated a factor of two increase in high-lift L/D in wind tunnel experiments. Circulation control can also be used for this purpose.

Supersonic large, long-range aircraft also require a focus on improvements of L/D. Options available include multi-body configurations and other configuration improvements, as well as supersonic laminar flow. Single-body configurations with L/Ds approaching 10 are under development in the NASA High Speed Research Program (HSR) and this program is also conducting flight tests to demonstrate the practical capability for supersonic laminar flow control. Technologies flowing out of this program could support the development of future long-range military transports or bombers, as depicted in Figure 2.1.3.

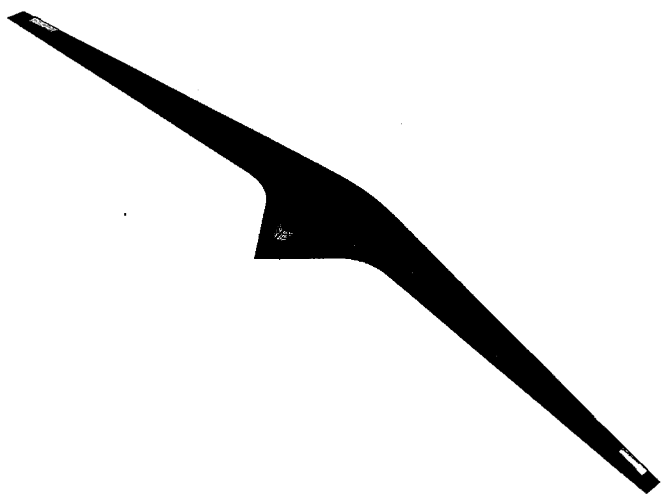


Figure 2.1.3 Future Long-Range Bomber Concept

Critical to developing aircraft of the size being discussed here is the adequacy of existing wind tunnels. Design of large transport aircraft has been plagued by the inability to accurately account for Reynolds number scaling effects from wind tunnel to flight. These inadequacies cause sometimes large, but always unquantifiable uncertainties in the cruise and high-lift performance of the aircraft. The new subsonic and transonic wind tunnels discussed in Section 3.1 are critical to reducing design uncertainty for this class of aircraft.

Propulsion

These aircraft will take advantage of performance gains being made in engine technology programs, especially IHPTET. These advanced engines with high thrust-to-weight ratios and low fuel consumption will provide an additive increment to range beyond that achieved through

higher L/D. These engines should also be more reliable, quieter, and have lower emissions. Beyond IHPTET the potential exists for very-low TSFC turbine engines which can further improve the range.

Supersonic aircraft require advances in turbojet engine technology to allow for high turbine inlet temperatures and low emissions. The NASA HSR program is scheduled to demonstrate these advances in ground tests by 2002.

Airframe Structures

Reduction in airframe structural weight can also contribute to increased range and payload capacity of future transport aircraft. The most significant advance in airframe structures available today is the use of composite materials in primary structure. Limited applications of composite structure are appearing in the most recent military and commercial transports and they form most of the structure of the B-2. The current NASA Advanced Composites Technology program is demonstrating advanced manufacturing techniques for constructing transport aircraft wing and fuselage structure along with demonstrating field repair techniques. ARPA is pursuing a composite structure manufacturing technology program under the Technology Reinvestment Program. As part of the NASA HSR, high temperature composites for supersonic aircraft application are being developed. These programs, along with service experience gained with the limited application of these technologies over the next five to ten years should render this technology mature. New, lighter-weight alloys such as aluminum-lithium offer a more conventional path to reducing airframe structural weight.

Smart materials and active load control can provide a positive impact on the performance of transport aircraft through the role they can play in flutter suppression. High-aspect-ratio composite wings will be very flexible and flutter suppression technology will be critical to achieving the complete performance envelope.

Design of the structure for this class of aircraft can be enhanced through the use of concurrent structural design technologies. These technologies should both reduce the time to design the structure and increase the quality of the design. Incorporation of health monitoring and diagnostics into the structure of the aircraft will enhance the ability to monitor the aging of the aircraft.

Flight Systems

The major improvements in flight systems technology for the future are associated with the flight deck as well as the aircraft control system. Future flight deck technologies include advanced external vision systems and other technologies to permit all weather operations with little or no degradation from VFR. The movement to the more electric aircraft will continue and evolve into a fly-by-light, power-by-wire (FBL/PBW) capability early in the next century. FBL/PBW should lead to lighter, more reliable aircraft. GPS-based navigation and guidance functions will be available in the near future, and even the world's civil air traffic control system will use this technology for "free-flight" operation. Virtual reality simulators will be available for pilot training and potentially for remote operation of these aircraft. Cognitive engineering technologies will advance to the point that most functions in the cockpit associated with aviating and navigating will be automated in a way that the human remains aware of the state of the aircraft and can safely intervene when required. While these flight-deck technologies do not

contribute to the performance of the aircraft itself, they should significantly contribute to the performance of the flight crew. For long (12,000 NM) flights, new flight-deck automation technologies and enhanced understanding of human factors could be used to counter human fatigue and deal with crew rest requirements.

Aircraft Subsystems

More electric aircraft technologies will contribute to the reliability, maintainability, and affordability of future large transport aircraft. Component life can be increased through management of heat loads in the aircraft using fuel cooling.

For aircraft with this large payload capability, consideration must be given to efficient means of loading and unloading. Research into automating and reducing the cycle time of these activities is critical, and concepts such as precision airdrop present an option for delivering payload in the field without landing. Other operational concerns center around airfield operations, which must accommodate the sheer size of the aircraft. Issues such as taxiway spacing from runways and near terminal operations might require incorporation of capabilities such as folding wings. The B777 was designed from the start to have the option for a folding wing, but to date no airline has ordered an aircraft so configured.

Future high-threat environments demand attention to survivability of large transport aircraft. The large volume of these aircraft and the potential to co-develop such aircraft for both military and civil use preclude stealth. However, this same large volume and payload carrying capability, along with high on-board power, indicate that laser weaponry could provide these vehicles with a shield against missile or aircraft attack. Long-range bombers could rely on a combination of stealth and laser weaponry.

Integration

Design of these aircraft in a fashion to ensure affordability will require the use of a new suite of design tools. These tools include cost modeling which accounts for the manufacturing process, training, and logistics support. The potential dual use of the vehicle makes application of advanced multidisciplinary design and manufacturing techniques attractive.

2.1.4 Operational Enhancements

A future generation large long-range aircraft should significantly reduce direct operating cost through lower maintenance requirements, less fuel burn per ton-mile, reduced logistics footprint, and reduced crew requirements through size-based productivity increases. Because of the unrefueled range of these aircraft, the cost of air refueling operations is eliminated. Operational capability can be further enhanced through active health monitoring systems, making possible a reliability-centered maintenance strategy.

2.1.5 Cost of Ownership Reduction

The major component of total aircraft related operating costs (TAROC) is the cost of ownership. The technologies discussed above will dramatically reduce the other components of TAROC including the direct operating costs and maintenance, increasing the proportion of TAROC associated with the cost of ownership. For military aircraft this factor is further

exaggerated due to the limited numbers of aircraft purchased and the limited operations per aircraft as compared to civil transports. This suggests that achieving an affordable next generation large transport aircraft requires innovative approaches to reducing cost of ownership. From a technological perspective, it appears that the period between 2010 and 2015 might be an ideal time to consider introduction of a next generation transport. The technologies required for the performance increases indicated above should be available with even a modestly funded research and development effort. That time period could also offer an opportunity for an unprecedented civil/military partnership to develop either a large transonic transport or supersonic transport. Recent market studies have indicated the need for a transonic civil freighter aircraft of the size discussed herein in the same time period. For this aircraft to be successful, it must capture the international market for freight worth over $10/pound. Aircraft with the performance capabilities indicated herein should have that capability. Moreover, with the advancement of just-in-time (JIT) delivery of parts to factories and the increased emphasis on rapid delivery to reduce inventory costs, the need for rapid freight movement will increase. It is even possible that short-field capability will be advantageous for these civil aircraft to allow them to make JIT deliveries and pickups directly at the factory. With the need for a civil aircraft with capabilities closely matching a military requirement, it appears advantageous to the United States to pursue a civil/military joint venture to develop a next generation large transport aircraft. This joint venture could be along the lines of the NASA HSR Program, where NASA and industry are jointly participating in technological risk reduction for a next generation supersonic transport. Then, industry is expected to develop, manufacture, and operate the vehicles as a commercial venture. For the case of the large transport aircraft, the USAF and industry could jointly pursue technological risk reduction, and the military could directly fund those technologies uniquely required by the military (if any). Once the technology risk is sufficiently reduced, industry could pursue the development of the commercial version of the aircraft and the Air Force could fund the development costs of the differences for its version. In this way the Air Force would share the development cost of the aircraft with the eventual commercial operators of this class of aircraft, which should significantly reduce the cost of ownership.

2.1.6 Technology Requirements

Table 2.1.2 summarizes the status of the technologies discussed above as important to future large transport aircraft with global range.

The System Priority and Technical Status category rankings of the matrix represent the overall evaluations of the Aircraft and Propulsion Panel integrated over the collection of technologies of each System Concept. Facility prioirty is shown where appropriate. The estimated time to availability shown in Technical Status is a judgment based upon the present level of understanding, the anticipated degree of difficulty of further development, and the assumption of reasonable/customary levels of investment.

Table 2.1.1 Future Large, Long-Range Aircraft Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support	A	2
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Modeling and Simulation	A	2
Test and Evaluation	Integrated Test, Simulation, and Computational Analysis	B	2
Aerodynamics			
Advanced Configurations	High Aspect Ratio/Strut-Braced Wings; Blended Wing/Body; Multiple Fuselages	A	2
Flow Control	Laminar Flow Control; Riblets; Micro-vortex Generators	B	2
Design Methods	Wind Tunnel Test Techniques; CFD	B	2
Facilities	Large, High Reynolds No., Subsonic and Transonic	B	2
Airbreathing Propulsion			
High Thrust-to-Weight Turbine Engines	High-Temperature Engine Materials and Structures; High Bypass Ratio; High Temperature Lubricants	B	2
Very-Low TSFC Turbine Engines	High-Temperature Engine Materials and Structures; High Bypass Ratio; High Temperature Lubricants	A	2
Structures			
Advanced Airframe Materials	Metallics; Advanced Composites; Advanced Lightweight Materials; High Temperature Materials	B	2
Adaptive Structures	Smart Materials; Active Load/Thermal Control	A	2
Configuration and Concept Design	Tailored Structures; Concurrent Design	A	2
Multi-Functional Structures	Health Monitoring and Diagnostics; "Smart Skins"	B	2
Facilities		C	1
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW	A	2
Human System Interface	External Vision; Displays	A	2
Multivariable Design Tools and Criteria	Multivariable Active Control; Cognitive Engineering-Based Criteria	B	2
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls	A	2
Aircraft Subsystems			
More Electric Aircraft	Light Weight High Power Converter Modules	A	2
Thermal Energy Management	Component Life; Reduced IR Signature, Thermal Management	B	2
Ground Operations	Cargo Handling	B	2
Energy Storage and Generation	Light Weight Batteries; Fuel Cells	A	2

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

2.2 Uninhabited Aircraft

2.2.1 Introduction

Uninhabited aircraft are those air vehicles that do not have on-board presence of a pilot or aircrew. All control functions normally associated with piloting are performed by on-board controllers. Information used by those controllers may be effected by humans off-board, providing input via data links (as depicted in Figure 2.2.1). Examples of input are target position designation, target prioritization, steering commands, three-axis flight control and throttle commands, consent command to release weapons, etc. These vehicles span the range from completely autonomous after launch (e.g., cruise missiles) to complete dependency on humans for some mission and/or flight critical functions (e.g., remotely piloted vehicles). Characteristics of systems over the range of concepts from missile to manned fighter are shown in Figure 2.2.2. The two columns on the left show the range of characteristics associated with uninhabited aircraft. The descriptor Unmanned Air Vehicles (UAVs) normally refers to single purpose aircraft while Unmanned Tactical Aircraft (UTA) refers to a more capable aircraft with capabilities more like today's fighter aircraft.

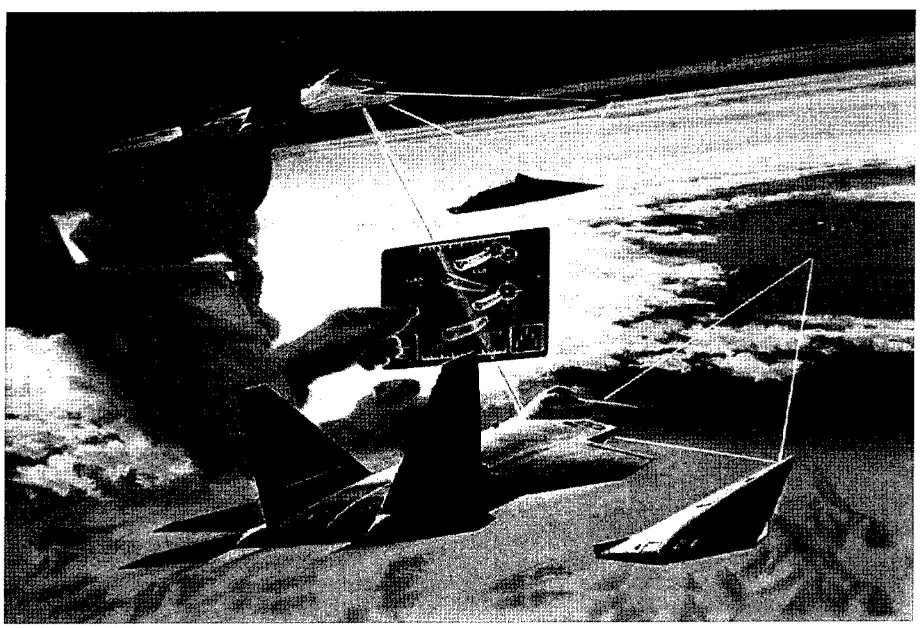
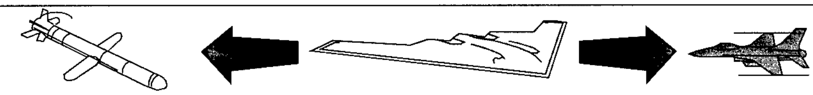


Figure 2.2.1 Example Employment of Uninhabited Aircraft

The determination of whether a vehicle should be uninhabited or not depends on the functional requirements it must perform in the overall warfighting system it plays in. The concept is that humans will be placed in critical functions and places where the overall warfighting system performs at its best. In some cases human presence on-board air vehicles may not be desired due to added cost or low probability of survival in the threat environment. During design of the overall warfighting system, the design trade-offs must take into account human mental and



MISSILE	UNINHABITED REUSABLE	MANNED FIGHTER
Launch Only	Launch and Recover	Launch and Recover
One Way	Two Way	Two Way
Autonomous/Self-Contained	Autonomous/Offboard Control	Onboard Control with Offboard Aids
Not Reusable	Reusable	Reusable
Wooden Round Storage	Wooden Round Storage	Not Stored
Simulator for Proficiency	Simulator for Proficiency	Proficiency Flying
Limited Post-Launch Adaptability	Adaptable to Post-Launch Tactical	Highly Adaptable to Tactical Situation Change
Safe Passage Concept	Safe Passage Concept	Safe Passage Concept
Time Deconflicted	IFF	IFF
	Position	Position
Position Reporting Not Required	Position Reporting Required	Position Reporting Required
Limited BDA	Inlimited BDA	BDA Not Popular
Range Limited to Fuel on Board	Range Not Limited to Fuel on Board or Pilot Endurance	Range Not Limited to Fuel on Board, Physiological Limits
No Mission Debrief	Factual Mission Debrief	Interpreted Factual Mission Debrief
Limited Warhead Selection	Unlimited Warhead Selection	Unlimited Warhead Selection
Limited Fault Tolerance	Fault Tolerance to One or Two Levels	Very Fault Tolerant to Multiple Features
Platform Consumed	Preplanned Fixed Targets	Preplanned Fixed Targets
Preplanned Fixed Targets	Weapons Consumed	Weapons Consumed
Limited Self Defense	Retargetable/Recallable/Retaskable	Retargetable/Recallable/Retaskable
Single Role	Countermeasures, BVR Missiles	Full Self Defense
	Multi-Role	Multi-Role

Figure 2.2.2 Example Characteristics of Manned and Uninhabited Aircraft.

physical capabilities, technologies to replicate or enhance those capabilities, the bandwidth limits for bringing data on-board versus transmitting data off-board, bandwidth capabilities of the human and displays, sensors and controllers which interface between humans and mechanical components of the system, ability to protect communications in a jamming or spoofing environment, etc.

2.2.2 Performance Potential

There is the potential for significant cost savings at the vehicle level and at the overall warfighting system level because of reduced crew training requirements and the ability to replace highly trained, multi-talented crew members with specialists (e.g., contractors). However, some individual uninhabited aircraft may require more support man-hours; for example, a long endurance sensor platform may require extended hours of sensor data analyses. In designing the overall mix of uninhabited and inhabited vehicles, the warfighting "system of systems" should be optimized from a performance and cost perspective.

The class of uninhabited aircraft associated with very complex tactical missions present a revolutionary approach for many high risk missions including SEAD, attack and kill of tactical threats, BDA, and even air combat. The UTA of the future could be a mixed fleet of manned and uninhabited attack vehicles or a totally uninhabited fleet controlled by a hierarchy of human "commanders," where at one level each commander controls a single vehicle (using virtual reality presentations and interfaces, for example) and at higher levels "commanders" control groups of aircraft through the single vehicle commander (see Figure 2.2.3). Preliminary cost benefit analyses indicate very large savings in O&S cost.

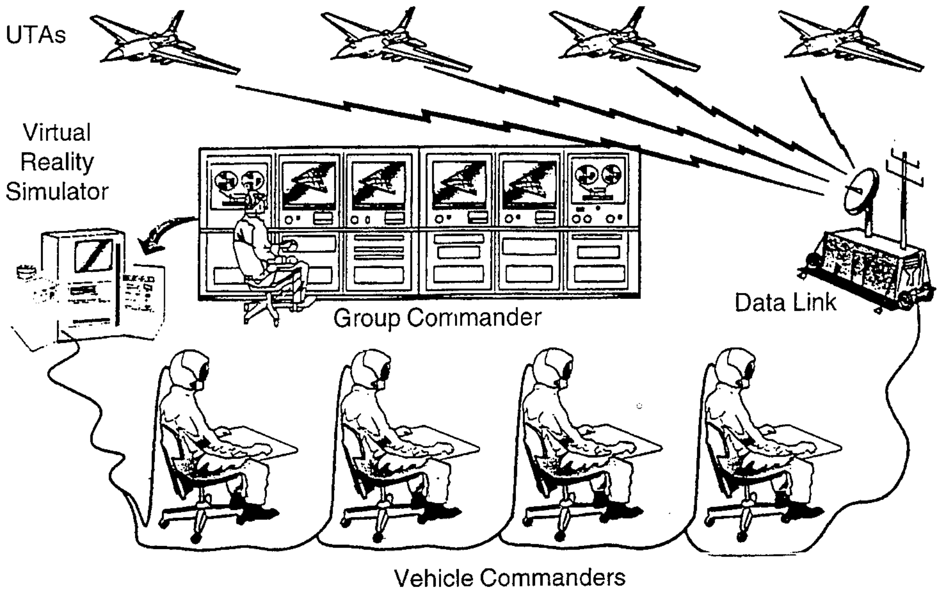


Figure 2.2.3 Virtual Reality Control of UTAs

Once human presence is removed from air vehicles, unique capabilities can be addressed such as very long endurance flight and miniaturization of vehicle sizes. The vehicles can also be flown in high threat/low probability of survival environments to deliver weapons to launch points, deliver cargo accurately, or perform high-risk development flight testing (e.g., X-aircraft). New approaches to launch and recovery can be pursued (e.g., from/to ground vehicles, aircraft carriers/ships, airborne vehicles (Section 2.7), ICBM's, and satellites).

Note that the air vehicle systems and structure can be designed for extremely high maneuver loads and agility. There are no crew-constrained g-limits (positive or negative), nor are there limits on agility or flying/handling qualities.

2.2.3 Enabling Technologies

The design and development of uninhabited aircraft depends on most of the tools and databases needed for inhabited vehicles, except that new tools and technologies are needed for those aircraft that are meant to fly beyond current vehicle operational envelopes (e.g., very high altitude/low speed cruise, very small/ miniaturized "microairvehicles," very high dynamic pressure cruise vehicles). In design, mission-dependent requirements must be met as usual for speed, altitude, range, lethality, survivability, flexibility, and affordability, plus the set of on-board control requirements (normally associated with human presence) must be addressed and met. Functions of off-board human controllers (if any) and the on-board automated systems must be defined and met.

The key technologies which enable this concept include:

- The enhanced technology of cognitive engineering which is needed to define functions of off-board human controllers and their interactions with on-board systems.
- Extensions of air vehicle technology to very small scales (e.g., aerodynamics scaled to lower Reynolds numbers, low-cost small propulsion systems, low-cost plastic/composite structure, and low-cost control/sensor/avionics subsystems).
- Extensions of aerodynamics, propulsion, structures, subsystem, controls, and avionics technologies beyond the current envelopes to very low dynamic pressure and high altitude, and to very high dynamic pressure and/or maneuver extremes.

Other technology developments which enable uninhabited vehicles include:

- Intelligent signal and data processing (e.g., using AI, neural network and fuzzy logic hardware and software) or by use of equivalent organic systems.
- Secure and possibly redundant control data link(s).
- Control science and applications for mission and vehicle management of a complex, highly coupled system.
- Control criteria to achieve optimal performance which is based on that used for missile control.

2.2.4 Technology Requirements

Refer to Table 2.2.1 for a summary of technologies critical to this concept and an estimate of their development status. Section 3.0 contains more detail.

Table 2.2.1 Future Uninhabited Vehicle Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support	A	2
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Design of Ultra-small Vehicles; Modeling and Simulation	A	2
Test and Evaluation	Integrated Test, Simulation, and Computational Analysis with Off-Board Systems, and Controllers	A	2
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW	A	2
Human System Interface	Integration with Off-Board Controllers and Cognitive Engineering	A	2
Multivariable Design Tools and Criteria	Multivariable Active Control; Control Laws for Expanded-Envelope Flight	A	2
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls	A	2

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

Note that Table 2.2.1 highlights the technologies unique to the uninhabited vehicle concept. Other technologies are important, but are dependent on the specific vehicle concept to be made uninhabited. Some set—such as aerodynamics, propulsion, and structures—associated with ultra-small vehicles, very long endurance high altitude flight, or very high dynamic pressure flight represent extensions to current vehicle performance envelopes. These require advances in those disciplines not specifically highlighted in this table. Refer to the attack aircraft, hypersonic vehicle, and long-endurance aircraft for insight into these other areas. Also, note that all uninhabited aircraft enabling technologies are forecast to be available within 5 to 15 years.

2.3 Special Operations

2.3.1 Introduction

We envision that the requirements for special operations will dramatically increase in the future. The need for flexible covert intervention in both developed and undeveloped nations around the world appears certain.

The basic workhorses of today's special operations forces (SOF) are the fixed-wing MC-130 and the rotary wing MH-53J and MH-60G helicopters. The CV-22 Osprey has some attractive special operations features, but they are insufficient to solve the problems faced by the USAF.

There is a need for a new, affordable, reliable, survivable SOF vehicle that has a range of 1500 NM, high subsonic flight speeds, the capability for VTOL/hover at the point of insertion and/or extraction, and low acoustic, visual, IR, and RF signatures. The payload for this vehicle would include a limited number of troops, a small personnel carrier, weapons, sensors, trans

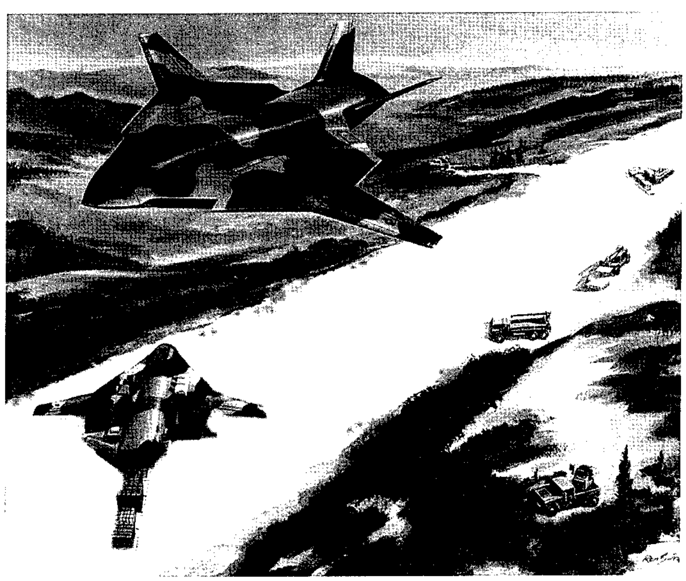


Figure 2.3.1 Conceptual Special Operations Aircraft

mitters, and so forth. A vehicle with all of these characteristics, such as that depicted in Figure 2.3.1, cannot be produced with the technology available now, but foreseeable improvements can make it possible. The important required technological advances are described below.

2.3.2 Technology Requirements

The key to meeting many of the SOF vehicle goals is airbreathing propulsion. Low specific fuel consumption increases range and payload and/or reduces gross takeoff weight. High thrust is required for VTOL/hover. Low fan noise and exhaust velocities reduce acoustic signatures. Low IR and RF signature treatments are achieved with the high compression ratio, high turbine inlet temperature, high bypass ratio, variable cycle, ducted turbofan engines that flow continuously from the IHPTET program (Section 3.2). Simplicity and reliability will be increased, and maintainability and vulnerability reduced, by using the more electric aircraft approach (Section 3.5.2). Reliability will also be improved by employing advanced digital engine controls that identify impending problems and provide the pilot with alternative strategies for returning safely home.

Modern aerodynamics, strongly buttressed by CFD, can produce vehicle configurations tailored to the SOF mission that provide an excellent combination of aerodynamic performance (high L/D), high lift (unpowered or powered), and low observability (Section 3.1). A special attribute of CFD is the ability to model the flow in regions of unfavorable aerodynamic interactions. The designer can then reconfigure or add flow control devices (or, possibly, MEMs) to produce favorable interactions.

Materials and structures advances are also critical to the success of an SOF vehicle because they reduce airframe structural weight , vulnerability, and IR and RF signatures. They are also essential to developing relatively lightweight components of the vehicle, such as damage tolerant turboprop blades, landing gears or landing systems, and armor or small arms fire protection (Section 3.3).

The VTOL/hover phase of flight is one of the most demanding for SOF vehicles. Many mechanical arrangements have already been shown to be feasible for providing vertical thrust or powered lift. For example, the Harrier uses fan stream thrust deflection, the Osprey uses wingtip mounted tilt rotors, and demonstrators have used separate fans driven by high pressure air or shaft power extracted from the main engine. Unfortunately, these schemes add considerable complexity and weight to the system. Consideration should therefore be given to innovative schemes that use the engine exhaust stream to create lift with fewer moving parts. An example of this is the "channel wing" (Figure 2.3.2), for which the lift is created by the high speed exhaust stream flowing over the concave or upper portion of the wing. In the case of a ducted turbofan, this can be facilitated by integrating the fan cowl or duct with the wing. The smaller jets necessary for stability and control can employ high pressure air bled from the compressor.

Affordability is enhanced by these technology advances in a number of ways. First, they reduce the gross takeoff weight and mechanical complexity—the prime drivers of initial, fuel, and maintenance costs. Second, along with the powerful onboard sensor and computational capabilities of the future (Section 3.4), they provide improved mission flexibility and autonomy, which reduces the need for other assets to complete the required missions. Third, they are

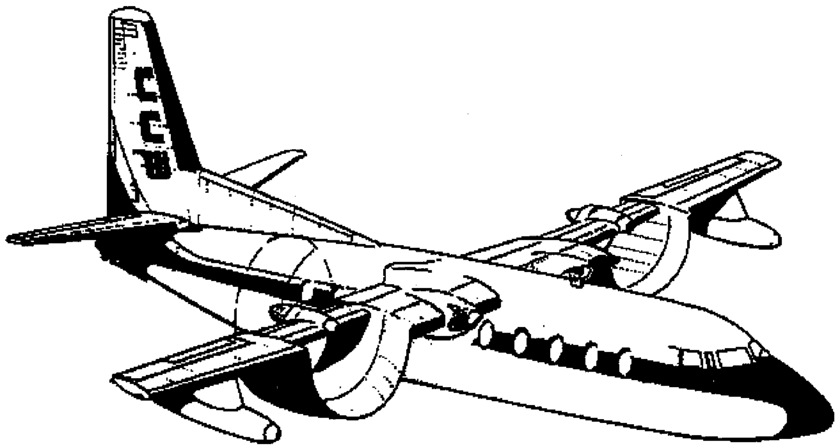


Figure 2.3.2 Channel Wing Aircraft

more survivable, reducing the number needed in the initial inventory for a given assessment of threat. Fourth, the technology advances are largely being carried out in response to other USAF requirements, and R&D funding is only necessary to adapt them to the SOF vehicle.

Technology efforts already in place, plus special attention to their peculiar needs, should make a substantially improved new generation of SOF vehicles possible within 5-10 years, and fully capable aircraft available within 20 years. Technologies critical to the development of special operations aircraft are summarized in Table 2.3.1.

The SOF mission will play a crucial role in the Air Force of the future. The SOF vehicle presents the aircraft designer with an extremely demanding set of specifications. The requirements for flexibility, reliability, survivability, and affordability are especially important.

Fortunately, technology efforts already underway can make available a substantially improved generation of STOL SOF vehicles in the 150-200 klbf class within 5-10 years. If the technology identified above is vigorously pursued, a fully capable SOF vehicle is possible within 15-20 years.

2.4 Long-Endurance Aircraft

2.4.1 Introduction

Multiple missions have been identified for uninhabited aircraft which can fly for very long periods of time (days to weeks or months) at ultra-high altitudes (above 80,000 feet). These missions include reconnaissance, environmental monitoring, communication, and weapons platforms. In addition, all of these missions have a low speed requirement, where low subsonic Mach numbers for travel from launch site to station are acceptable. Because of the high altitude/autonomous system requirements, this is a difficult mission. Fortunately, the enabling technologies for development are beginning to appear.

Table 2.3.1 Future Special Operations Vehicle Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Training and Logistics Support	B	2
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability	A	2
Test and Evaluation	Integrated Test and Simulation	B	2
Aerodynamics			
Advanced Configurations	High Subsonic L/D; Low Observables; Channel Wing	B	2
Flow Control	Low Drag; Supercirculation	B	1
Design Methods	CFD	B	2
Facilities		C	1
Airbreathing Propulsion			
High Thrust-to-Weight Turbine Engines	Variable Cycle Engine; Low Observables	A	2
Very-Low TSFC Turbine Engines	Low Fuel Consumption	B	2
Powered Lift	Vectored Thrust; Lift Fans; Nozzles	A	2
Facilities	Powered Lift	B	1
Structures			
Advanced Airframe Materials	Lightweight Materials; Survivability; Low Observables	A	1
High-Temperature Airframe Materials	Exhaust Impingement	A	2
Adaptive Structures	Active Load Control	B	2
Configuration and Concept Design	Tailored Structures	A	2
Multi-Functional Structures	Condition and Health Monitoring; Compensating Structures	B	2
Facilities		C	1
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control; FBL/PBW	A	2
Human System Interface	External Vision; Displays	B	2
Multivariable Design Tools and Criteria	Multivariable Active Control	B	2
Fault Diagnostics and In-Flight Reconfiguration	Health and Condition Monitoring; In-Flight Fault Isolation; Automated Reconfigurable Controls	A	2
Aircraft Subsystems			
More Electric Aircraft	Integrated Aircraft Subsystems; Reliability; Flexibility; Survivability	A	2
Thermal Energy Management	Increased Component Life; Low Observables	B	1
Transparencies	Aircrew safety/effectiveness	B	1
Ground Operations	Cargo Delivery and Recovery; Landing Gear	B	1

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

High-Altitude, Long-Endurance (HALE) aircraft, such as depicted in Figure 2.4.1, can be categorized into three different classes depending on their operational altitude and endurance requirements.

Figure 2.4.1 Conceptual High-Altitude, Long-Endurance Aircraft

As indicated in Table 2.4.1, above 50,000 ft the slow speed of the aircraft and the low density of the atmosphere result in aircraft powered by reciprocating engines with propellers because they are smaller and lighter than the turbojet. Above 80,000 ft the low atmospheric density does not allow enough cooling for a turbocharged engine, so electric propulsion must be used. In addition, the long duration missions preclude carrying large amounts of fuel onboard.

Table 2.4.1 HALE Requirements by Operational Type

Altitude	Endurance	Propulsion	Example
Low (<50,000 ft.)	Hours	Turbofan	Tier 3- aircraft
High (50,000 to 80,000 ft.)	Days	Turbocharged piston/ Propeller	German Strato 2C
Ultra-high (above 80,000 ft.)	Months	Electric/Propeller	Pathfinder

The power requirements for a propeller driven aircraft show that required engine power decreases with wing span, but increases with

- gross weight
- wing loading (weight/wing area)
- wetted area
- altitude

As a result, HALE aircraft will be large and probably look like flying wings.

In recent years several aircraft have been, or are, under development which serve to demonstrate the feasibility of aircraft of the type required. The experimental Pathfinder aircraft is a solar-powered, propeller-driven vehicle designed to demonstrate the technologies for an operational aircraft with a duration of 2000-3000 hours at altitudes greater than 70,000 feet. This solar powered aircraft is a descendent of the Solar Challenger aircraft which flew from Paris to London.

A more conventional turbocharger-powered aircraft, the Strato 2C, is currently under development in Germany and has been flown successfully. This aircraft is designed for atmospheric sampling with a four-person crew. It is designed to fly for eight hours at an altitude of 80,000 feet, has a range of 4000 miles and a payload of 2200 pounds (including the air crew). Both the Pathfinder and the Strato 2C take advantage of modern composite materials to reduce the structural weight fraction and also to accommodate very high-aspect-ratio wings for aerodynamic efficiency.

The required mission performance parameters of the HALE aircraft are as follows.

2.4.2 Technology Requirements

Table 2.4.2 HALE Mission Performance Parameters

Performance Parameter	HALE Requirement
Payload	2000 pounds
Endurance	Indefinite
Speed	Low Subsonic
Altitude	above 80,000 feet

Aerodynamics

High L/D configurations are a requirement for achieving the required endurance. The combination of a high-aspect-ratio wing planform (AR>20) combined with low Reynolds number natural laminar flow airfoils will provide acceptable aerodynamic performance. Span-loading configurations such as that represented by the Pathfinder aircraft are attractive because of lower wetted areas than similar fuselage/wing designs. The Pathfinder experimental aircraft can be viewed as a multi-body configuration, although it currently has no payload carrying capability. Its six engines are located across the entire span of the wing. Strut bracing, possibly with lifting struts, could create high wing bending/torsion stiffness for the high-aspect-ratios required.

Propulsion and Power

The ultra-high altitude HALE's most attractive propulsion option is the electric motor driven propeller. The long-endurance and low-weight requirement eliminates batteries as a primary power source. The use of solar cells to supply the propulsive power has been demonstrated to be feasible today on the Solar Challenger and Pathfinder aircraft.

Traditional electric motors are heavy and hot. However, advanced electric motors are available today. New electric motors with efficiencies of over 90% and weights about 1/4 that of similar motors are now available. High efficiency reduces (but doesn't eliminate) the need for large heat exchangers for cooling and reduces the requirement for solar power and battery storage. These motors come in sizes as large as 70 hp with a volume about the size of a small automobile tire.

To increase the payload capability of an airplane like Pathfinder, the development of solar cells with conversion efficiencies greater than 20% and 80% reduction in cell weight is required and feasible within the next twenty years. A key technology for this aircraft will be the development of efficient solar cell material that can be sprayed onto the aircraft surface. Spraying a solar converter onto the aircraft skin instead of bonding current technology solar cells will simplify the process of mounting conformable solar collectors on the large wing surface and allow solar collection on multiple surfaces. However, heat rejection remains a problem to be addressed creatively.

Solar powered aircraft will need a means of storing energy during the day to power the engines at night. Possible options include rechargeable batteries, fuel cells, or flywheels. Additionally, in the reconnaissance or sampling mode, power will be required to operate the sensors, processors, and transmitters. Sufficient solar power in excess of that required to power the propulsion system over a twenty-four hour period will be required to power the sensor payload. This power could be drawn from the energy storage system.

Structures

High specific strength and specific stiffness materials are required because of the aerodynamic requirement for surface smoothness to maintain laminar flow and the need for a low structural weight fraction and high energy storage weight. Stiffness requirements outweigh

strength requirements so that active control of flutter may be necessary unless an overdesigned structure is acceptable. Specific strength and stiffness requirements lead to the desirability of composite materials for the structure.

Controls and Displays

Because of the multi-role mission, the HALE vehicle is likely to be a modular vehicle. This modular vehicle would have a distributed control system connected to a master control system via a bus. Reprogrammable control modules would be required both for the modules and the master control system. The concept of modular HALE aircraft is discussed further below.

The combination of low speed flight at high CL, and very flexible structure leads to a requirement for autonomous active control of vehicle attitude (including maneuvering flight) and structural response to atmospheric disturbances. The recent advances in active, adaptable materials such as piezoelectric materials indicate that they can control undesirable loads and furnish maneuvering ability without heavy control linkages. The long duration of the mission demands the capability for autonomous operation over long periods of time, interspersed with ground or sensor package generated commands for specific activities or maneuvers.

Operational Considerations

Modularity of these aircraft can enhance operational flexibility. The Pathfinder aircraft is currently designed in a modular fashion, with each module providing unique capability. For the class of aircraft under discussion here, propulsion modules, weapons modules, sensor modules, etc., are a possibility. Configurations suitable for each mission could be assembled from such modules in the field.

These aircraft have very unconventional operating requirements and characteristics. They will take a long time to reach operating altitude and arrive on station. Takeoff weather requirements will be stringent unless the vehicle flight system can compensate for gusts. Current aircraft of this class require low winds over the runway and aloft because of their low wing loading and structural flexibility of the wing. In addition, because the high altitude requirement drives the wing design to one with low wing loading, the aircraft will have to avoid storms and other high wind situations in the lower atmosphere during climb. Climb rates will further be restricted to minimize ice accumulation. Once at altitude the aircraft may take a few days to arrive on-station if it is based in the CONUS.

Controlling the landing of an aircraft with a high span and low wing loading is also difficult since the wing operates in ground effect as it approaches the runway. These requirements call for innovative operational techniques and may require technologies to be developed such as deployment from conventional aircraft, rocket launch, landing on a moving vehicle, etc. Folding the aircraft would be required for launch by either an aircraft or rocket, and shape memory materials may be useful for this purpose.

The HALE aircraft concept has several items that depend strongly upon technology development. The most serious of these is the electrical power supply. The vehicle must be closely integrated in its functions and it is a prime candidate for multi-disciplinary optimization. The technology assessments for this aircraft are presented in Table 2.4.3.

Table 2.4.3 Future Long-Endurance Vehicle Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, and Logistics	B	2
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Modeling and Simulation	A	2
Test and Evaluation	Integrated Test, Simulation, and Computational Analysis	B	2
Aerodynamics			
Advanced Configurations	High Aspect Ratio/Strut-Braced Wings; High q/Low Altitude	A	2
Flow Control	Laminar Flow Control; Riblets; Micro-vortex Generators	C	2
Design Methods	Wind Tunnel Test Techniques; CFD	B	1
Airbreathing Propulsion			
HALE Propulsion System	Electrical Motor or Turboboost Reciprocating Engine	A	2
Structures			
Advanced Airframe Materials	Advanced Composites; Advanced Lightweight Materials	A	1
Adaptive Structures	Active Load Control; Smart Materials	B	3
Configuration and Concept Design	Tailored Structures; Concurrent Design	A	2
Multi-Functional Structures	Health Monitoring and Diagnostics; "Smart Skins"	B	2
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control of Flight and Avionics; FBL/PBW	A	2
Human System Interface	Integration with Off-Board Controllers; Flight Sensors Field-of-View	C	2
Multivariable Design Tools and Criteria	Multivariable Active Control	B	2
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls	A	2
Aircraft Subsystems			
Thermal Energy Management	Solar Cell Cooling; Avionics Cooling; Reduced IR Signature	A	2
Energy Storage and Generation	Batteries; Solar Cells; Flywheels; Fuel Cells	A	3

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

2.5 Modular Vehicles

2.5.1 Introduction

The concept of a modular vehicle is an extension of the "avionics common module concept" to a full-up air vehicle system, as depicted in Figure 2.5.1. It includes three levels of modularity which can be designed into a vehicle from the onset or selectively introduced into existing vehicles via planned retrofits. These three levels are manufacturing level, depot level, and flightline level. At the manufacturing level, the aircraft and the manufacturing processes are designed to tailor aircraft fabrication and assembly so that some modules are permanently

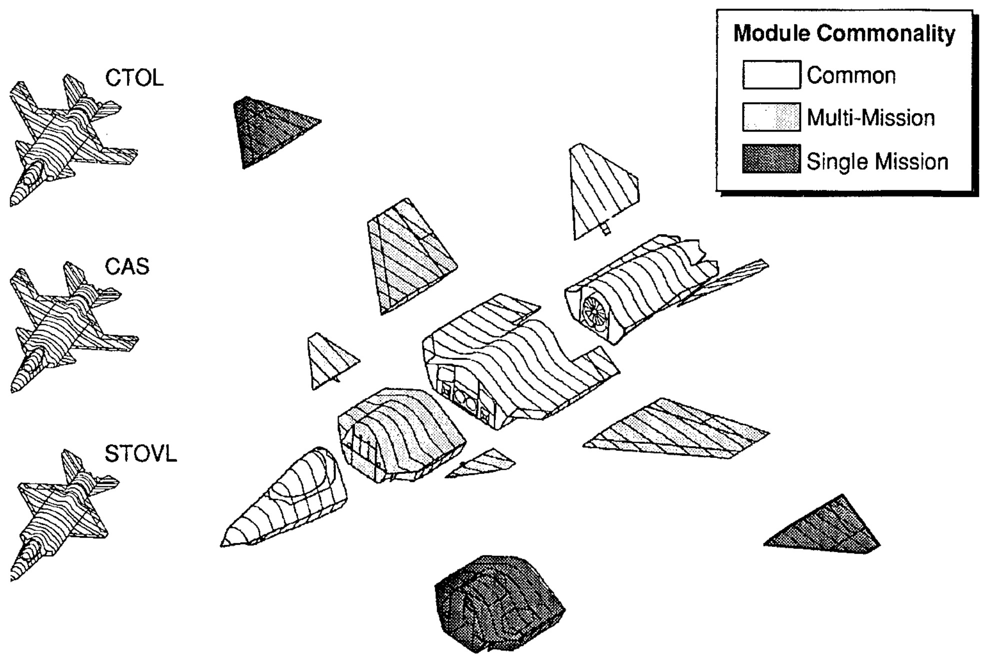


Figure 2.5.1 Modular Air Vehicle Concept

built-in on the production line. For example, the first aircraft on a line may be assembled with a strong keel and support structure and a carrier-capable landing gear module to become aircraft carrier capable. The second aircraft could be assembled without the special keel, structure, and with a low energy landing gear module. A third aircraft could have carrier capability plus unique avionics apertures built into the wing leading edge. At this level, unique modules intended for permanent installation or for depot level change-out are installed. At the depot level of modularity, one could find replacement of a fuel tank module with a lift-fan module or replacement of a long-range transonic cruise wing with a shorter-range supersonic cruise version, and/or major upgrade of avionics core processing modules and racks. At the flightline level of modularity one would find provisions to install mission-unique avionics (e.g., modular radome), weapons, external pods, and engine(s), or a fuel tank/uninhabited control module in lieu of a cockpit module. Some modules will be "turned around" for reuse between missions faster than the aircraft.

Examples of modules include avionics hardware and software, payload/weapons, cockpit modules (displays, controllers, "unmanned modules," pilot sensors, HMDs, etc.), engines, wings (tailored for cruise with external carriage, high-speed dash, maneuver, LO, etc.), and subsystem modules (electric power generation, internal rail weapon launchers, etc.). The module concept relates to classes of vehicles where families of modules can best accommodate needs within a given class of aircraft.

The modular concept is timely for several reasons:

- It formally acknowledges the need to design-in provisions to accept periodic (and frequent) avionics upgrades.
- It recognizes the need to affordably accept upgrades of hydro/electrical/mechanical subsystems, engines, and sensors/apertures less frequently than other (digital avionics hardware and software) upgrades.
- It applies to all classes of air vehicles (fighters, transports, helicopters) and can be made compatible with land and water borne vehicle modularity.

2.5.2 Performance Potential

The objective of the modular concept is to lower overall life cycle costs while building in flexibility. These are done by:

- Tailoring aircraft capabilities by using modules for specific mission needs.
- Accommodating a flow of product improvement upgrade modules for avionics, displays, weapons subsystems, engines, and selected structural components during the long life of the basic airframe structure.
- Designing-in fault isolation and diagnostics, and convenient access to modules to reduce mean time to remove and replace them.
- Putting in place the logistics infrastructure to handle modules which are common across many weapons systems and can be shipped overnight to provide just-in-time mission capability.

As the modularity concept evolves, one would expect to see more modularity at the flight-line level and less at depot and manufacturing levels.

Studies on the JAST concepts have shown that the modular concept has the potential to reduce acquisition and O&S costs each by up to 50 percent in avionics, airframe, engine, and subsystems categories.

2.5.3 Enabling Technical Advances

The modular concept requires new design tools, including definitions of standard interfaces so that all modules can be specified for form, fit, and functionality and be competitively procured to encourage miniaturization, innovation, and low cost. Commercial standards and architectures are used where available. For example, cargo containers used by transports will follow the commercial standard.

The modular concept will affect the logistics system by transforming a system of vehicle-unique parts and spares towards one that is common-module dominated with focus on module functionality for use by many weapon systems. Modules will be designed for no unscheduled maintenance and for self-diagnostics. As elements of integrated vehicle fault diagnostics systems, they will indicate their health for preflight and post-flight analysis so that, with failures, vehicle systems can reconfigure in-flight and failures will be isolated to the individual module.

Modules will be individually tracked by the logistics system and have the capability to store ID data and relevant time histories of key parameters such as those reflecting performance under environmental stress.

Pre-mission planning will include a definition of required modules due to threat, target, weather, and other information/intelligence. Modules (hardware and software) must be selected to meet the mission requirements of avoiding enemy detection, detecting and recognizing threats and targets, destroying or neutralizing threats and targets, and interacting with other assets (ground, air, sea, space). Uncertainty in mission requirements may require extra modules to provide flexibility to react to real-time redirection, anticipated pop-up threats or targets, and to cover critical uncertainties. Mission planning will depend on new sets of criteria to help aircrews and mission planner decide on the mission (module) configuration. Aircraft configuration control systems must be adapted to this concept and made flexible to accept mission-to-mission changes while tracking current air vehicle capability in a disciplined way.

Training for each mission will take into account the specific module configurations of all vehicles and off-board systems that will be interacting during the mission. Training for aircrew and maintenance crews will take on a new dimension due to the flexibility provided by modular systems. In fact, training curricula must also be modular in an architecture that is strongly tied to air vehicle module architectures.

Technologies which enable the modular concept are exemplified by those which pace the commercial personal computing sector (i.e., processor and memory hardware, operating system, and applications software). Air vehicle system designers need new design databases and tools to do the design tradeoffs that take into account cost and performance issues of manufacturing, depot, and flightline modularity. The JAST program is developing much of this. However, the concept must evolve in a deliberate way—via a national strategy and programs—which is driven primarily by affordability.

2.5.4 Technology Requirements

Table 2.5.1 lists the technologies needed to enable modular vehicle design and manufacture, and indicates their criticality to the modular concept and their technical development status. Refer to each technology in Section 3 for more details.

Note that Table 2.5.1 highlights the technologies unique to the modular concept. Other technologies such as aerodynamic flow control and design methods, propulsion with powered lift, structural materials, adaptive and multifunction structures, control design tools and criteria, subsystem heat load management, and integration T&E are also important, but dependent on the specific vehicle concept to be made modular. There is expected synergy between the modular unique technologies and mission-driven unique technologies that must be exploited during design. Furthermore, the modular concept is best exploited by spreading appropriate modules across many vehicle types.

"Common modules" are evolving now from core avionics, control digital hardware and software, communications, navigation, and displays as well as sensor processors and shared function sensors. Modules for propulsion systems, aircraft subsystems, and control actuators to wings, tails, fuselage components, cockpits, etc. should evolve. An affordability-based strategy should drive that evolution. It should also spread across the services.

Table 2.5.1 Future Modular Vehicle Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Detailed Module Cost Models: Vehicle, Module Manufacturing Process, Training (with Module Configurations), and Logistics Support of Modules	A	2
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability with Modules; Multidisciplinary Design Optimization; Module Production; Modeling and Simulation (to include Cost)	A	2
Aerodynamics			
Advanced Configurations	Low Observables; Design of Modular Wings, Tails, and Fuselage Sections	A	2
Airbreathing Propulsion			
High Thrust-to-Weight Turbine Engines	Variable Cycle Engine; Design of Inlet and Nozzle Modules	A	2
Structures			
Configuration and Concept Design	Tailored Structures; Concurrent Design; Load-Sharing by Modules	A	2
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW	A	2
Human System Interface	Field-of-View Sensors; Display Presentation Format; Integration with Off-Board Controllers; Cockpit Modules	A	2
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls to Account for Module Configuration	A	2
Aircraft Subsystems			
More Electric Aircraft	Light Weight, High Power Modular Subsystem Components	A	2
Thermal Management	Avionics, Cockpit, Sensors, Weapons, Skin, and Engine Thermal Management Modules	A	2
Ground Operations	System Change-out; Module Handling	A	2

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

Note that all modular vehicle enabling technologies are forecast to be available within 5 to 15 years.

2.6 Hypersonic Vehicles

2.6.1 Introduction

Sustained hypersonic flight offers potential revolutionary improvements in future war-fighting and space launch capabilities. For example, hypersonic attack missiles could provide exceptionally rapid response by striking time-critical targets 750 miles away in less than 10 minutes. Similarly, Mach 8 to 10 global reach aircraft (as depicted in Figure 2.6.1) based in CONUS, could strike or obtain recce/intel data on any significant military target on the globe

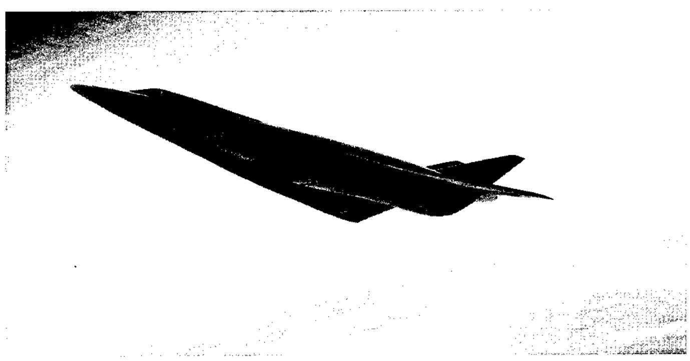


Figure 2.6.1 Conceptual Hypersonic Aircraft

within two hours. The ability to launch military payloads into any appropriate orbit also will greatly enhance warfighter effectiveness and combat flexibility. Hypersonic speeds greatly enhance both survivability by practically eliminating enemy defensive capabilities and lethality.

2.6.2 Hypersonic Concepts

Missiles

Within the next 10 years, hypersonic missiles can be developed that can accelerate to Mach numbers of 6 to 8 and cruise for several hundred miles to a target (ground or air) within 10 to 15 minutes from launch. Ground impact velocities of Mach 4 to 5 are achievable if the missile is powered in the terminal phase of flight. The preferred propulsion system for this class missile is either an airbreathing ramjet/scramjet or a ducted rocket because the higher specific impulse (up to three times pure rocket fuel specific impulse) greatly reduces the launch weight, which allows the missile to be launched from tactical aircraft (e.g., F-15, F-22) as well as from bombers.

Maneuvering Re-entry Vehicle (MRV)

At the higher end of the Mach-altitude spectrum is a hypersonic maneuvering re-entry vehicle (MRV), a missile which is boosted to Mach 15 to 20 with an ICBM/IRBM, separated at about 150,000 ft altitude and glides to the target with a large area footprint (3,000 miles cross range/10,000 miles downrange) from the insertion point as a result of a lift/drag ratio at M=20 of approximately 3.0. There is no propulsion system on the missile (it's all in the booster), and Mach 4 to 6 impact velocity can be achieved to penetrate deeply-buried targets. Accurate targeting is provided by a terminal phase sensor, such as a conformal synthetic array radar coupled with a GPS-based guidance system.

Rapid Response/Global Reach Aircraft System

By about 2010 to 2020, the technology can be developed for a global range (once around the earth) hypersonic transatmospheric aircraft which flies up to Mach 16 to 18 on an airbreathing (scramjet) propulsion system to reach any point on earth and return to base in CONUS in less than two hours. The entire surface of the globe can be covered by variations in launch

azimuth and route selection. Range can possibly be extended by skipping in and out of the atmosphere. The missions would include force projection (missiles, laser weapon) against ground, air or space targets, global recce/intel on short notice, or deployment of a payload to space in a staging maneuver. An all-rocket propulsion is more near term, but will result in a much larger vehicle.

A family of global reach aircraft can be designed with lower Mach number capability and less than total global range (for example, Mach 8 to 12 with about 10,000 mile range or Mach 6 to 8 with about 8,000 miles range). For flight speeds above approximately Mach 8, hydrogen fuel is required. Below Mach 8, advanced hydrocarbon-based fuels (e.g., endothermic reaction) will provide sufficient cooling and thrust. The higher density of hydrocarbon fuels compared to hydrogen results in a smaller (and possibly cheaper) aircraft for the same mission requirements. Hydrocarbon-fueled aircraft can be more easily integrated into the existing Air Force basing and logistics infrastructure.

Space Launch/Support

The rapid response/global reach high speed aircraft described above could be the basis of a reusable launch vehicle (RLV) system to deliver payloads to orbit on short notice with flexibility of orbital inclination, orbital altitude, and with re-entry from any low earth orbit in one revolution to return to its CONUS base. The most flexibility of launch operations for a given launch weight will come from an air-breathing system because of the higher specific impulse, compared to rockets. Higher specific impulse in the engine reduces the need for ultra-lightweight structures. Structures and subsystems can thus be designed for more robust "airframe-like" operations. Rocket propulsion system is more near-term, as evidenced by the current NASA X-33 RLV program. The biggest challenge in the X-33, or any single-stage rocket, will be to achieve a very high (about 0.90) propellant fraction. Thus, the structure must be very light so that flexibility, resilience, and maintenance will continue to be problems.

The hypersonic RLV system to support Air Force needs for on-demand, all azimuth, low cost launch of medium-mass (up to 25,000 lbs[3]) payloads to LEO can be approached from several design options, which require further study. Some options obviously require more technology development than others, but they generally offer lower operational and life cycle costs or more operational flexibility. Design options include:

- Staging: multiple (2 or 3) or single
- Take-off/Landing:

  -Horizontal takeoff from ground or air launch

  -Vertical takeoff/vertical or horizontal landing
- Propulsion:

  -All rocket

  -Rocket/airbreather

3. Space Technology Panel Report, Section 2.1, Launch Vehicle Technologies

-Hybrid (rocket-based combined cycle)

-Airbreather accelerator with rocket for orbital insertion

- Fuels:

-Hydrocarbon endothermic up to limit of cooling capacity

-Cryogenic hydrogen where required for cooling

A first-generation Air Force RLV system, developed in conjunction with NASA, can be available within 10 years with rocket propulsion, then evolved over the following 10 to 15 years toward increased use of airbreathing propulsion, advanced fuels, materials/structures, etc., to provide enhanced capabilities to meet AF/NASA launch and space support requirements. In the far-term (beyond 2025), innovative propulsion, aerodynamics, and structural concepts are possible which will further reduce RLV weight, size, cost for a given payload to space, or further increase operational flexibility and effectiveness.

2.6.3 Technology Requirements

A wide spectrum of technologies will be required to enable the development of the hypersonic vehicles for the missions described above. The matrix of Table 2.6.1 is provided in order to allow the reader to correlate the enabling technologies with the desired missions. They have been collected into their convenient and traditional groups of aerodynamics, propulsion fuels, and structures (including materials), and will be discussed here in that order.

Aerodynamics

Aerodynamic advancements needed are a function of vehicle application, speed, and configuration. For Mach 6 to 8 missiles, for example, the issue is aerodynamic efficiency (lift/drag) in a small, compact package with small control surfaces. For the maneuvering reentry vehicle (MRV), the issue is obtaining an L/D of at least 3.0 at Mach 20, with as low a level of aerodynamic heating as possible. For the global reach aircraft, which requires high cruise efficiency, the aerodynamic challenge is low drag and high L/D at the design cruise Mach number, along with a shape that minimizes aerodynamic heating, especially unwanted aerodynamic interference heating. Finally, for the RLV accelerator vehicles, the aerodynamic challenge is low drag (for reduced DV to reach orbit) and low aerodynamic heating. Aerodynamics, of course, includes the aerodynamics of control systems and the integration of propulsion elements, specifically the engine inlet and nozzle, with the airframe aerodynamics to achieve total vehicle design objectives. A key issue is the precise control of the vehicle steady state and dynamic attitude (angle of attack) in the high dynamic pressure regime of hypersonic flight.

The ability to achieve the aerodynamic design goals for hypersonic vehicles is currently limited by our understanding of chemically reacting gas flows, turbulence, and other hypersonic flow phenomena. We are not only limited in our ability to compute hypersonic flow fields across the complete range of Mach numbers of interest, we are severely handicapped in simulating these flows in ground test facilities (Section 4.1.3). Currently our capability to simulate hypersonic flows with the right gas chemistry, true temperature, and pressure is limited to the Mach 6 to Mach 8 flight regime.

Table 2.6.1 Technologies and Associated Mach Number Range

	Missiles (Accelerators)	Maneuvering Reentry Vehicles (Accelerators)	Rapid Response/ Global Reach Aircraft Systems (Cruisers)	Space Launch Support (Accelerators)
Mach Number	1-6	0-20	0-18	0-25
Enabling Technologies				
Aerodynamics	-High Lift/Drag Ratio -Low Drag -Airframe-Propulsion Integration -Controls	-High Lift/Drag -Minimal Aero Heating -Flow Modification	-Low Drag -Airframe-Prop Integration -High L/D -Control Effectiveness -Flow Modification	-Low Drag -Airframe-Prop Integration -Low Aero Heating -Control Effectiveness -Flow Modification
Propulsion	-Rocket -Dual-Mode Ramjet/Scramjet	-Rocket	-Rocket -Combined Cycle -Dual-Mode Ramjet/Scramjet -External Burning	-Rocket -Combined Cycle -Dual-Mode Ramjet/Scramjet -External Burning
Fuels	-Hydrocarbon -Endothermic HC		-Hydrocarbon -Endothermic HC -Hydrogen	-Hydrocarbon -Endothermic HC -Hydrogen
Structures	-Heat Sink -Ablatives	-Thermal Protection -Radiation Cooled	-Fuel Cooled -Radiation Cooled -Long Life Structure	-Fuel Cooled -Radiation Cooled -Low Structural Weight Fraction

The actual design will require precise location of the boundary layer transition point over the trajectory to be able to provide adequate cooling without excessive weight growth. Further, the coupling of aero-thermal-elastic effects with the problems of controlling the aircraft impose constraints on the flight management system. As a consequence, a long-term well funded research program is require to properly address these constraints.

Airbreathing Propulsion

Whenever possible, it is desirable to consider employing airbreathing propulsion because the oxygen for the combustion of the fuel and the mass for momentum reaction are obtained from the atmosphere rather than having to be carried along in place of payload or structure. It is also desirable to have all propulsion devices share a common flowpath (including inlet and exit) in order to simplify integration with the airframe and reduce the drag and weight associated with the propulsion system.

The choice of a propulsion system depends primarily on the flight Mach number (M). At subsonic speeds ($0 < M < 1$), and particularly when static ($M = 0$), ramjets and scramjets cannot provide adequate thrust because there is insufficient ram compression. Under these conditions, alternate propulsion devices must be used. One of these might be a parent aircraft that carries the vehicle aloft and releases it at high velocity, as is often the case for missiles. Another concept is the combined cycle engine, which behaves as a conventional turbofan or turbojet under static conditions and gradually transitions to a ramjet as the flight Mach number increases. The turboramjet and airturboramjet are variations on this theme.

High inlet stagnation temperatures limit combined cycle engines to flight Mach numbers less than about 3.5. Another approach is to use rockets either separately or installed within the ramjet/scramjet duct, in which case they are known as ducted rockets or rocket ejectors.

The transonic drag rise near M = 1 is often the sizing point for the engine unless supplementary thrust, such as external burning, is provided.

The ramjet, in which the flow is brought almost to rest in the combustor, is the propulsion device of choice for supersonic Mach numbers up to the hypersonic boundary of about 5-6. For hypersonic Mach numbers, the internal flow cannot be stagnated without causing unwanted dissociation of the air and internal pressures that necessitate heavy structures. Consequently, in hypersonic flight the internal flow is everywhere supersonic and the propulsion devices are known as scramjets (for "supersonic combustion ramjets"). Fortunately, through proper manipulation of fuel injection, a single device with few moving parts and no physical nozzle throat, known as the dual-mode ramjet/scramjet, can cover the entire supersonic spectrum.

As the flight Mach number and altitude increase and the air thins, the airbreathing engines provide less thrust and must eventually be augmented by thrust generated by fuel and oxidizer carried along. This thrust may again be either generated within the existing duct or by a separate rocket engine. The oxygen may be either stored from the beginning of flight or, when hydrogen is available as a heat sink, obtained from the atmospheric air by liquefaction and collected.

By combining these and other similar combustion engines, it is possible to produce thrust abundantly and efficiently over any Mach number range. The wider the range, of course, the more types of propulsion must be included and the premium on ingenious integration increases.

Fuels

The energy content of fuels is the primary consideration for hypersonic propulsion applications. Fortunately, both ordinary liquid hydrocarbons and liquid/slush hydrogen provide adequate energy for most applications. The next most important property of fuels is their cooling capacity because the heat loads at hypersonic speeds are enormous.

The very large cooling capacity of liquid/slush hydrogen is sufficient to cool the engine and external surfaces of practical vehicles to any desired flight Mach number. Unfortunately, the very low density of hydrogen causes the volume of the vehicle to be much larger than it would be for liquid hydrocarbon fuels. This, in turn, increases the drag, weight, and initial and support costs of the vehicle. The weight and costs are also increased because hydrogen is a cryogenic fluid that requires special tankage and handling. It is obviously desirable, therefore, to use liquid hydrocarbon fuels whenever possible.

For typical fuel-cooled aircraft and missile designs, the physical cooling capacity of liquid hydrocarbons can support Mach numbers up to about 4-5. Endothermic hydrocarbon fuels, for which the heat capacity is greatly increased by using absorbed heat to break the chemical bonds and produce smaller molecules, can support flight Mach numbers up to about 6-8. The endothermic fuels have the additional advantage of providing the combustor with compounds that are easier to mix and burn than the original composition.

Table 2.6.2 Hypersonic Vehicle Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support	A	3
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Modeling and Simulation	A	2
Test and Evaluation	Integrated Test, Simulation, and Computational Analysis	B	2-3
Aerodynamics			
Advanced Configurations	Waverider/Body; Hypersonic L/D	B	2
Flow Control	Transition Control	B	3
Design Methods	Wind Tunnel Test Techniques; CFD	A	2
Facilities	Hypersonic Aero Facilities	A	2
Airbreathing Propulsion			
Combined Cycle Engines		A	2
Dual-Mode Ramjet/ Scramjet		A	2-3
External Burning		C	2
Facilities	Realistic Test Conditions	A	2-3
Structures			
Advanced Airframe Materials	Metallics; Advanced Composites; Advanced Lightweight Materials	A	2
High-Temperature Airframe Materials	Hypersonic Airframes; Exhaust Impingement Structures	A	2
Adaptive Structures	Smart Materials; Active Load/Thermal Control	A	2
Configuration and Concept Design	Tailored Structures; Concurrent Design	A	2
Multi-Functional Structures	Health Monitoring and Diagnostics; "Smart Skins"	B	2
Facilities		A	2
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW	A	1
Human System Interface	External Vision; Displays; Integration with Off-Board Controllers	B	2
Multivariable Design Tools and Criteria	Multivariable Active Control; Cognitive Engineering-Based Criteria; Control Laws for Expanded-Envelope Flight	A	2
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls	A	2
Aircraft Subsystems			
Thermal Energy Management	Component Life	A	2
Endothermic Fuels		A	2
Ground Operations	Takeoff and Landing Systems	A	2
Air Crew Escape	Aircrew Safety/Effectiveness	A	2

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

Structures

High temperature materials will be critical for hypersonic flight. In addition, the importance of ensuring a small structural weight fraction coupled with the extremely harsh aerothermodynamic environment means that these materials must be light weight and have strength at extremely high temperatures. Many candidate materials are legacies of the NASP program. For some short endurance high Mach number missions, the use of ablatives will permit active and/or hydrogen cooling to be avoided.

Two types of materials are attractive for high temperature use, but neither is at the stage that they can fulfill the mission with the reliability required. The first of these materials is a class known as ceramic matrix composites (CMC). These materials have high specific strength and stiffness and excellent retention of these properties at high temperatures (about 2000°F). Monolithic ceramics are brittle and sensitive to small defects. To remedy this, CMC use fiber reinforcements (such as silicon carbide fibers) in a ceramic matrix such as alumina, silicon carbide or silicon nitride. These fiber reinforcements may be continuous, chopped fiber, small whiskers, or small particulates. Reinforcement tends to improve strain-to-failure properties. Unfortunately these materials are expensive to make, difficult to fabricate, and currently have low reliability.

Carbon/carbon (C/C) composites are the other material for hypersonic systems. This composite provides a low specific strength and stiffness with very high temperature operational capability. C/C materials have several problems that limit their current use. C/C oxidizes at temperatures as low as 800°F and must have a coating or oxidation protection system. Carbon/carbon materials are also difficult to join to other parts. Rocket nozzle and re-entry vehicle use has resulted in costs as much s $800/pound. Long range research and development for both of these materials is not being adequately addressed by either industry or government.

Table 2.6.2 summarizes the status of the key technologies discussed above and others as important to the development of hypersonic vehicles.

Revolutionary air vehicle capability is possible through exploration of hypersonic technologies. Future systems that reach out thousands of miles in less than an hour are possible, giving the Air Force true global reach/global power projection. A near term hypersonic application is a fast-response missile to attack time-critical targets with a stand-off range of several hundred miles. Such a system will help to develop key technologies in hypersonic propulsion, aerodynamics, and structures that can eventually lead to a global hypersonic capability and a low-cost reusable launch vehicle with airplane-like operation to reach earth orbit.

2.7 Future Attack/Aircraft

2.7.1 Introduction

By approximately 2025 a new type of low-cost, low observable small attack aircraft[4] (Figure 2.7.1) can be developed which will be able to deliver brilliant, low signature weapons to surface or subsurface targets. It could be piloted or unpiloted, in two different variants. Cost of the aircraft would be minimized by the small size of the aircraft, modular design, smart aircraft

4. Attack Panel Report, Section 6.0, Potential Revolutionary Concepts

components, system level integration of technologies, and transfer of avionics functions to sensors and systems off-board the attack aircraft. The small attack aircraft is envisioned to have a Mach 2 dash capability and an unrefueled radius of about 200 to 400 NM. This vehicle would have an extremely low radar cross section over a very wide frequency range; an extremely low, geometrically unique, and spectrally tailored infrared signature; a very low visual signature; essentially no electromagnetic emissions; a very low acoustic signature; and only passive sensors. Maneuverability of the manned version is in the F-22 class, with 50% to 100% higher g-loading in the unpiloted variant.

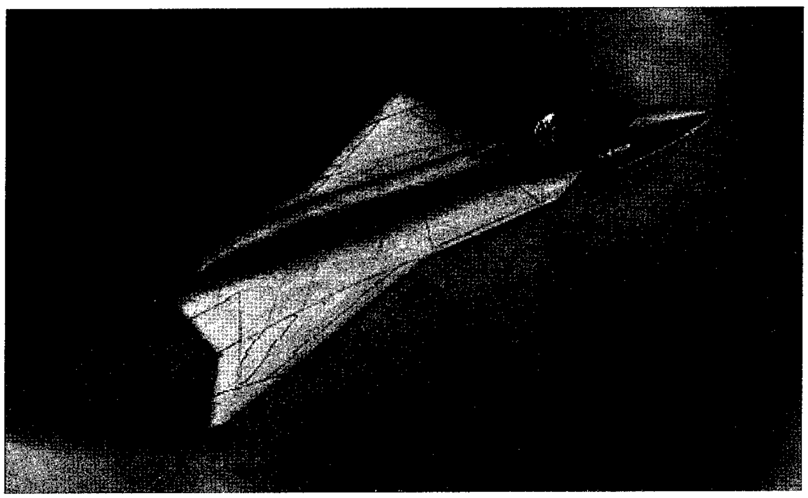


Figure 2.7.1 Conceptual Future Attack Aircraft

The extraordinary attack capability of this aircraft will be enhanced by its survivability. By the use of high powered laser and microwave defensive weapons[5], the aircraft will be invulnerable to attacking surface-to-air and air-to-air missiles at distances of 1 to 3 km from the aircraft. This defensive shield minimizes the surface-to-air and air-to-air threat. Complete spherical coverage around the aircraft can be defended by very rapid, agile maneuvers of the aircraft to provide line-of-sight aiming of the laser/microwave weapons. Since the shield is relatively close-in, an automated missile avoidance maneuver will be required. Of course, if the adversary develops laser or microwave weapons to attack this aircraft, suitable defenses, hardening, or countermeasures would be required.

The affordability goal of 10 to 20 million dollars fly-away cost (1996 dollars) will come from the fact that this will be a small aircraft (less than 20,000 lbs with weapons) since it will either operate close to the targets or be deployed from large transport aircraft (but not recovered to the mother ship), which will greatly reduce the range requirements, hence the size of the aircraft. Some lightness can be sacrificed to reduce cost of manufacturing and life cycle cost.

5. Directed Energy Panel Report, Section 2.10, Aircraft Self-Defense

Further affordability gains are from austere avionics, off-board sensors, small, powerful engines, advanced manufacturing principles, and multi-disciplinary integration. The airframe will have minimal logistics support through built-in health monitoring/diagnostic systems to indicate needed maintenance. The airframe structure will have an extraordinarily long life due to advanced materials.

Multiple roles, such as defensive counter-air, ground target attack, BDA, recce, or even limited special operations can be accomplished. Another multi-role characteristic will be to operate in a vertical landing mode, with vertical takeoff at light fuel load. This will enhance operational flexibility, allow the aircraft to get up close (within 200 NM), and even allow for limited special operations to be performed by the pilot.

2.7.2 Technology Requirements

The key technology is the development of the laser/microwave defensive shield.[6] Two alternative paths for the laser shield are being pursued and these are described in the Directed Energy Panel Report. One approach to the shield is based on phased arrays of laser diodes mounted in the skin of the aircraft.[7] The alternate (and more mature) approach is through the diode pumping of solid state lasers whose beam is then projected from pods above and below the aircraft. The prime power required for either of these alternatives is something less than 400 kilowatts which should be available from the engine, but power conditioning to provide low voltage high current input to the diodes will be necessary. High power microwave weapons will require about the same power but do not require the low voltage conversion. Microwaves provide an all weather solution and do not require the precision pointing and tracking required for lasers, but do require significant investment in electrical design and shielding to preclude fratricide or suicide. To be effective, the power, volume, and weight of the defensive shield will have to be reasonable, say a few cubic feet and a few hundred pounds. A large amount (up to one to two megawatts) of electrical energy is available directly from the aircraft engine which could allow operation of the laser and/or microwave defensive shield.

Aerodynamics

The future attack aircraft will be shaped for high transient maneuverability, low observables (especially infra-red), and deployability in a transport aircraft. Improved computational fluid dynamics will be used to design the aircraft configuration.

Airbreathing Propulsion

High T/W engines will reduce overall aircraft size and weight to meet the required performance goals. High combustion temperatures will eliminate the need for afterburning, and variable cycle features will further minimize the IR signature. The nozzle will be fixed area with pitch/yaw vectoring, but simple and low cost through use of fluidic area control and vector control.

6. Ibid

7. Directed Energy Panel Report, Section 2.13, FotoFighter

Table 2.7.1. Critical Future Attack Aircraft Technologies

Technology	Examples	Priority	Status
Integration			
Design Tools for Affordability	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support	A	2
Vehicle and Manufacturing Process Design Methods	Design for Manufacturability; Multidisciplinary Design Optimization; Design of Ultrasmall Vehicles; Modeling and Simulation	A	2
Test and Evaluation	Integrated Test, Simulation, and Computational Analysis	B	2
Aerodynamics			
Advanced Configurations	Blended Wing/Body; Low Observables; High q/Low Altitude	B	2
Flow Control	Vortex Flow Control; Micro-vortex Generators	B	2
Design Methods	Wind Tunnel Test Techniques; CFD	B	2
Facilities	Subsonic and Transonic	C	1
Airbreathing Propulsion			
High Thrust-to-Weight Turbine Engines	High-Temperature Engine Materials and Structures; Variable Cycle Engine; High Temperature Lubricants; Integral Starter/Generator; Fluidic Nozzle Control	A	2
Powered Lift	STOVL Engine-Airframe Integration	B	2
Structures			
Advanced Airframe Materials	Metallics; Advanced Composites; Advanced Lightweight Materials	A	2
High-Temperature Airframe Materials	Exhaust Impingement Structures	B	2
Adaptive Structures	Smart Materials; Active Load/Thermal Control; Flutter Suppression	B	2
Configuration and Concept Design	Tailored Structures; Concurrent Design	A	2
Multi-Functional Structures	Health Monitoring and Diagnostics; "Smart Skins"	B	2
Facilities		C	1
Vehicle Control			
Integrated Control System Architecture	Autonomous Active Control of Flight, Avionics, Engines, Structure, and Subsystems; Flowfield; FBL/PBW	A	2
Human System Interface	External Vision; Displays; Integration with Off-Board Controllers; Laser Eye Protection	A	2
Multivariable Design Tools and Criteria	Multivariable Active Control; Cognitive Engineering-Based Criteria; Control Laws for Expanded-Envelope Flight	B	2
Fault Diagnostics and In-Flight Reconfiguration	In-Flight Aircraft Health Monitoring and Diagnostics; Automated Reconfigurable Controls	A	2
Aircraft Subsystems			
More Electric Aircraft	Power Management for Active Defensive Systems; Energy Storage and Generation	A	2
Thermal Energy Management	Component Life; Reduced IR Signature; Thermal Management of Heat From Laser or Microwave Weapon	A	2
Ground Operations	System Change-out; Cargo Handling; Takeoff and Landing Systems	B	2
Transparencies	Low Cost, Multi-Functional Transparencies	B	2
Air Crew Escape	Aircrew safety/effectiveness	A	2

Key:

System Priority	Facility Priority	Technology Status
A-Must Have	A-New Are Needed	1-Potential Availability Now-5 Yrs
B-Enhances Performance/Cost	B-Major Upgrade	2- Potential Availability 5-15 Yrs
C-May be "Traded Out"	C-Existing Are OK	3- Potential Availability 15+ Yrs

Powered lift propulsion for vertical operations will be built into the engine system. A modular lift engine will be used if necessary to provide vertical takeoff and landing capability at a light fuel load (reduced range).

Structures

Light-weight, low cost structures will be important to meeting range/payload and maneuverability goals with a low (less than 20,000 lbs) takeoff weight. Adaptive structure (e.g., active aeroelastic wing), load control, flutter suppression, and smart skins will be used to reduce weight.

Control/Integration

Software reconfiguration of avionics, fire control, flight characteristics, and by on-board reconfiguration through smart structures/smart skins, pneumatic flow control, and micro-electromechanical machines (MEMs) will enhance operational effectiveness. Further reconfiguration of functionality during flight would come from reconfigurable cockpit, display, and information systems.

Other key technologies will be austere avionics, display, fire/flight control adaptability for the aircraft to operate in the dual role of manned or unmanned. When unmanned, the aircraft will be permitted to fly a more severe envelope and additional fuel or weapons can be added (Section 2.5).

Table 2.7.1 summarizes the key airframe and propulsion technologies and their status which are important to the future attack aircraft.

2.7.3 Summary

A revolutionary future attack aircraft that is small (less than 20,000 lbs), with a fly-away cost of 10-20 million dollars (1996) will be possible by about 2025. It will incorporate built-in lethal self-defense capability based on laser and/or microwave active countermeasures that, when combined with enhanced aircraft agility, will make the aircraft virtually invulnerable to attack while it is performing its mission. This aircraft will be rapidly deployed world-wide on a large transport aircraft to provide rapid response to crisis situations without the need for an air base infrastructure. A modular lift engine will provide vertical/ultra-short take-off and landing capability when needed.

2.8 Technology Summary

The following matrices present a summary of the key technologies related to the seven concepts. A discussion of these technologies is given in Section 3. A discussion on the supporting infrastructure is provided in Section 4. Specific sections are noted in brackets under the appropriate Technology.

The System Priority and Technical Status category rankings of the matrix represent the overall evaluations of the Aircraft and Propulsion Panel integrated over the collection of technologies of each System Concept. With regard to System Priority, it is necessary to distinguish the special case of Facility Priority, as shown parenthetically. The estimated time to availability shown in Technical Status is a judgment based upon the present level of understanding, the anticipated degree of difficulty of further development, and the assumption of reasonable/customary levels of investment.

Table 2.8.1 Technology Status and System Priority

Technology	Examples	Modular Vehicle		Uninhabited Aircraft		Hypersonic Vehicles		Attack Aircraft		Large, Long-Range Aircraft		Special Operations		Long Endurance Aircraft	
		SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS
Integration															
Design Tools for Affordability [3.6.1]	Cost Models: Vehicle, Manufacturing Process, Training, and Logistics Support	A	2	A	2	A	3	A	2	A	2	B	2	B	2
Vehicle and Manufacturing Process Design Methods [3.6.2]	Design for Manufacturability; Multidisciplinary Design Optimization; Design of Ultrasmall Vehicles; Modeling and Simulation	A	2	A	2	A	2	A	2	A	2	A	2	A	2
Test and Evaluation [3.6.3	Integrated Test, Simulation, and Computational Analysis			A	2	A	2-3	B	2	B	2	B	2	B	2

Shading
Light = N/A
Dark = Depends on Specific Vehicle Application

System (Facility) Priority (SP)
A - Must Have (New Are Needed)
B - Enhances Performance/Cost (Major Upgrade Needed)
C - May be "Traded Out" (Existing Are OK)

Technical Status (TS)
1 - Potential Availability Now-5 Yrs
2 - Potential Availability 5-15 Yrs
3 - Potential Availability 15+ Yrs

Technology	Examples	Modular Vehicle		Uninhabited Aircraft		Hypersonic Vehicles		Attack Aircraft		Large, Long-Range Aircraft		Special Operations		Long Endurance Aircraft	
		SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS
Aerodynamics															
Advanced Configurations [3.1.2, 3.1.5]	High Aspect Ratio/Strut-Braced Wings; Blended Wing/Body; Low Observables; Hypersonic L/D; High q/Low Altitude	A	2			B	2	B	2	A	2	A	2	A	2
Flow Control [3.1.4, 3.1.5]	Laminar Flow Control; Riblets; Micro-vortex Generators					B	3	B	2	B	2	B	1	C	2
Design Methods [3.1.4, 3.1.5]	Aerothermodynamic Analysis; Wind Tunnel Test Techniques; CFD					A	2	B	2	B	2	B	2	B	1
Facilities [4.1.3, 4.1.4]	Large, High Reynolds #, Subsonic and Transonic					A	2	C	1	B	2	C	1	C	1

Shading
Light = N/A
Dark = Depends on Specific Vehicle Application

System (Facility) Priority (SP)
A - Must Have (New Are Needed)
B - Enhances Performance/Cost (Major Upgrade Needed)
C - May be "Traded Out" (Existing Are OK)

Technical Status (TS)
1 - Potential Availability Now-5 Yrs
2 - Potential Availability 5-15 Yrs
3 - Potential Availability 15+ Yrs

Table 2.8.1 Technology Status and System Priority (continued)

Technology	Examples	Modular Vehicle		Uninhabited Aircraft		Hypersonic Vehicles		Attack Aircraft		Large, Long-Range Aircraft		Special Operations		Long Endurance Aircraft	
	System/Concept	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS
Airbreathing Propulsion															
High Thrust-to-Weight Turbine Engines [3.2.2]	High-Temperature Engine Materials and Structures; High Cycle Fatigue; High Temperature Lubricants; Variable Cycle Engine	A	2					A	2	B	2	A	2		
Very-Low TSFC Turbine Engines [3.2.2]	High-Temperature Engine Materials and Structures; High Cycle Fatigue; High Temperature Lubricants									A	2	B	2		
Powered Lift [3.2.2]	VSTOL Engine-Airframe Integration							B	2			A	2		
Combined Cycle Engines [3.2.3]						A	2								
Dual-Mode Ramjet/Scramjet [3.2.3]						A	2-3								
HALE Propulsion System [2.7.2]														A	2
Facilities [4.1.3]	Hypersonic Airbreathing					A	2-3	C	1	C	1	B	1	C	1

Shading
Light = N/A
Dark = Depends on Specific Vehicle Application

System (Facility) Priority (SP)
A - Must Have (New Are Needed)
B - Enhances Performance/Cost (Major Upgrade Needed)
C - May be "Traded Out" (Existing Are OK)

Technical Status (TS)
1 - Potential Availability Now-5 Yrs
2 - Potential Availability 5-15 Yrs
3 - Potential Availability 15+ Yrs

Technology	Examples	Modular Vehicle		Uninhabited Aircraft		Hypersonic Vehicles		Attack Aircraft		Large, Long-Range Aircraft		Special Operations		Long Endurance Aircraft	
	System/Concept	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS
Structures															
Advanced Airframe Materials [3.3.2]	Metallics; Advanced Composites; Advanced Lightweight Materials					A	2	A	2	B	2	A	1	A	1
High-Temperature Airframe Materials [3.3.5]	Hypersonic Airframes; Exhaust Impingement					A	2	B	2			A	2		
Adaptive Structures [3.3.3]	Smart Materials; Active Load/Thermal Control					A	2	B	2	A	2	B	2	B	3
Configuration and Concept Design [3.3.2]	Tailored Structures; Concurrent Design	A	2			A	2	A	2	A	2	A	2	A	2
Multi-Functional Structures [3.3.3]	Health Monitoring and Diagnostics; "Smart Skins"					B	2	B	2	B	2	B	2	B	2
Facilities [4.1.3]						A	2	C	1	C	1	C	1	C	1

Shading
Light = N/A
Dark = Depends on Specific Vehicle Application

System (Facility) Priority (SP)
A - Must Have (New Are Needed)
B - Enhances Performance/Cost (Major Upgrade Needed)
C - May be "Traded Out" (Existing Are OK)

Technical Status (TS)
1 - Potential Availability Now-5 Yrs
2 - Potential Availability 5-15 Yrs
3 - Potential Availability 15+ Yrs

Table 2.8.1 Technology Status and System Priority (continued)

Technology	Examples	Modular Vehicle		Uninhabited Aircraft		Hypersonic Vehicles		Attack Aircraft		Large, Long-Range Aircraft		Special Operations		Long Endurance Aircraft	
	System/Concept	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS
Vehicle Control															
Integrated Control System Architecture [3.4.2]	Autonomous Active Control of Flight, Avionics, Engines, and Subsystems, Flowfield, and Structure; FBL/PBW	A	2	A	2	A	2	A	2	A	2	A	2	A	2
Human System Interface [3.4.3]	External Vision; Displays; Integration with Off-Board Controllers	A	2	A	2	B	2	A	2	A	2	B	2	C	2
Multivariable Design Tools and Criteria [3.4.3]	Multivariable Active Control; Cognitive Engineering-Based Criteria; Control Laws for Expanded-Envelope Flight			A	2	A	2	B	2	B	2	B	2	B	2
Fault Diagnostics and In-Flight Reconfiguration [3.4.3]	In-Flight Fault Isolation; Automated Reconfigurable Controls	A	2	A	2	A	2	A	2	A	2	A	2	A	2

Shading
Light = N/A
Dark = Depends on Specific Vehicle Application

System (Facility) Priority (SP)
A - Must Have (New Are Needed)
B - Enhances Performance/Cost (Major Upgrade Needed)
C - May be "Traded Out" (Existing Are OK)

Technical Status (TS)
1 - Potential Availability Now-5 Yrs
2 - Potential Availability 5-15 Yrs
3 - Potential Availability 15+ Yrs

Technology	Examples	Modular Vehicle		Uninhabited Aircraft		Hypersonic Vehicles		Attack Aircraft		Large, Long-Range Aircraft		Special Operations		Long Endurance Aircraft	
	System/Concept	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS	SP	TS
Aircraft Subsystems															
More Electric Aircraft [3.5.2]		A	2					A	2	A	2	A	2		
Thermal Energy Management [3.5.5]	Component Life; Reduced IR Signature					A	2	A	2	B	2	B	1	A	2
Endothermic Fuels [3.5.3]						A	2								
Ground Operations [3.5.6]	System Change-out; Cargo Handling	A	2			A	2	B	2	B	2	B	1		
Transparencies [3.5.7]	Aircrew safety/effectiveness							B	2			B	1		
Air Crew Escape [3.5.8]						B	2	A	2						
Energy Storage and Generation [3.5.2]	Batteries; Solar Cells; Aircraft Defensive Systems									A	2			A	3

Shading
Light = N/A
Dark = Depends on Specific Vehicle Application

System (Facility) Priority (SP)
A - Must Have (New Are Needed)
B - Enhances Performance/Cost (Major Upgrade Needed)
C - May be "Traded Out" (Existing Are OK)

Technical Status (TS)
1 - Potential Availability Now-5 Yrs
2 - Potential Availability 5-15 Yrs
3 - Potential Availability 15+ Yrs

3.0 Enabling Technologies

The following subsections present an assessment of the state of the art for the key air vehicle technologies. Areas of potential advancement are identified and, in some cases, research steps are suggested.

3.1 Aerodynamics

3.1.1 Introduction

The development of aerodynamic technology has been hampered by the fact that this field of mechanics is dominated by nonlinearity. This has forced the aerodynamicist to rely heavily on experimental methods and approximate theoretical techniques. The dominant theoretical approximation of this field has been to neglect the influence of viscosity and hence much of the focus in aerodynamic technology development was to understand and take advantage of inviscid flow phenomena and to minimize the effects of viscosity in the flowfield. This mind set was evident in the original von Karman report which emphasized the development of an experimental facility base aimed at understanding, accounting for, and manipulating the effects of the inviscid phenomenon of compressibility.

Three developments have brought the focus of attention in aerodynamics to the understanding and manipulation of viscous flow phenomena. The most important development is the need to remove uncertainty in the design process of aircraft as ever more aggressive performance requirements are placed on new designs and development costs continue to rise. The major uncertainty in the aerodynamic design process today is that of Reynolds number, a measure of the relative importance of viscous flow phenomena. A recent example of this uncertainty was the misprediction of wing trailing-edge drag in the design of the C-17 which turned out to be a Reynolds number scaling error. The second development has been the maturation of computational fluid dynamics (CFD) for inviscid flows. These methods can now predict the nonlinear, inviscid aerodynamics of arbitrarily complex aircraft geometries quite efficiently. The state of development of CFD for viscous flows is not nearly so mature, and major uncertainties exist with this technology in predicting the effects of Reynolds number. The third development is the introduction of new wind tunnel technologies that greatly increase Reynolds number simulation capability. This capability, which today exists for up to transonic Mach numbers, is expensive compared to conventional wind tunnel technology, and their extreme environments make testing difficult. Summarizing today's situation, a strong engineering need exists for improved viscous flow design tools, computational methodology still lacks the required capability to meet this need, and a limited new facility capability to predict viscous effects up to flight Reynolds numbers exists to partially fill this need.

Table 3.1.1 summarizes aerodynamics technology requirements from the vehicle technologies tables of Section 2.

The technical shortfalls in advanced configurations are vehicle dependent. The ability to develop the configurations required in each vehicle class is dependent on the other three areas. For example, flow control technologies can be used to gain the advantage predicted by favorable inviscid interference effects that previously could not be achieved due to viscous flow phenomena. Improved design methods which accurately account for the effects of viscosity

Table 3.1.1 Aerodynamic Technology Requirements for Vehicle Classes

	System Priority			
Vehicle Class	**Advanced Configurations**	**Flow Control**	**Design Methods**	**Facilities**
Large, Long-Range Aircraft	1	2	2	2
Uninhabited Aircraft	D	D	D	D
Special Operations	2	2	2	3
Long-Endurance Aircraft	1	3	2	3
Modular Vehicles	1	D	1	D
Hypersonic Vehicles	2	2	1	1
Future Attack Aircraft	2	2	2	3

Key: 1-Critical; 2-Enhances Performance/Cost; 3-May be "Traded Out"; D-Application dependent

can avoid future errors of the type made on the C-17 for conventional configurations and are imperative for advanced configurations which rely on control of both favorable and unfavorable flow phenomena. Development of facilities to meet future Air Force requirements is discussed in Section 4.1. In order to support the development of advanced configurations, flow control technologies, and improved design methods, basic research in the physics of poorly understood flow phenomena is required. The discussion below is organized around the first three bullets above, followed by a discussion of required basic physics research. This section ends with the identification of potential breakthrough research areas in aerodynamics.

3.1.2 Advanced Configuration Research

Advanced configuration research and development has been a neglected field over recent years, although some highly specialized configuration concepts have appeared. Some work in advanced configurations has been conducted for fighter aircraft aimed at increased maneuverability. Additionally, aerodynamic designs for LO aircraft have been developed which provide vehicle shapes which minimize signature. For large aircraft, the B-2 bomber's flying wing configuration represents a modern application of a concept developed in the 1940's and 50's.

With the advent of modern CFD (Section 3.1.4) and enhanced flow control technologies (Section 3.1.3), the opportunity exists for a renaissance in advanced configuration research. There are numerous "advanced configuration technologies" discussed in Section 2 of this report, but most of these ideas were developed in previous decades and not pursued for numerous reasons. These reasons include inadequate design tools and databases, stability and control

(which can now be successfully addressed in combination with modern structures and control technologies), and a lack of overall development and practical demonstration. The potential for radically new configuration concepts exists with the new ability CFD provides of exploring and predicting favorable nonlinear interference effects, and technologies for controlling vortices, viscous flow effects, and separation.

A focused effort in advanced configuration research should thus proceed along two fronts. The first front would involve systematic investigation of previously proposed concepts. For subsonic aircraft these concepts include strut braced wings, spanloaders, channel wings, multi-fuselage aircraft, and others. For supersonic aircraft, exploration of configurations which reduce drag through favorable interference have been proposed but not systematically investigated. The second front would be an Edisonian investigation of radically different concepts, particularly ones which simultaneously take advantage of flow control technologies and modern structural and control concepts. Ideas here might include development of composite wing surfaces with "built-in" suction systems for laminar flow control; smart surfaces which are used to control vortices and boundary layers; Goldschmied airfoils which synergistically combine laminar flow control, propulsion, and structural design; and many others. New missions such as those made possible by the development of uninhabited aircraft will require development of new configuration concepts specialized for high-dynamic-pressure/low-altitude and low-dynamic-pressure/high-altitude flight. Configuration concepts that allow maneuvering at high angle of attack and high turn rates will also be important to future uninhabited aircraft. Also of particular importance in this area is the development of hypersonic configuration options that provide high L/D and low drag at high Mach numbers with or without fully integrated airbreathing propulsion systems. These hypersonic configuration concepts must be developed in a fashion to minimize transonic drag.

Research in advanced aerodynamic configurations in the future must proceed along a multidisciplinary path. Early conceptualization of new configurations must include considerations of propulsion integration as well as structures and control concepts. The development of the design integration technologies discussed in Section 3.6 will allow rapid analysis of new concepts in this fashion.

Such a program of advanced configuration research would open up new possibilities for aircraft performance and perhaps develop new applications. Further, it should serve as guidance for research in more fundamental areas such as flow control , design methods, and cross disciplinary couplings such that all of the supporting technologies for the advanced configurations could be matured simultaneously. Viewed in this light, advanced configuration research would again assume its role as the driver of aerodynamic technology development.

3.1.3 Flow Control

The major categories of flow control requiring further research and development are fluidic control, vortex control, viscous control, and separation control. Many concepts in this general area have been around for years, but, again, the advent of CFD and modern flowfield measurement technology enable their practical development.

Fluidic control could be particularly useful for exhaust nozzle area control and thrust vectoring. The basic physical concepts have been demonstrated, and continuation of current focused efforts at practical application are required. Substantial reductions in nozzle weight and

observability along with cost reduction are the payoffs. Fluidic control could be of potential value for uninhabited aircraft, multi-role aircraft, and hypersonic vehicles.

Several options for vortex control have been proposed and require further development. New innovative opportunities exist. Pneumatic control of vortices can be used to generate control forces and moments. Improvements of 25% in turn rates have been indicated from such devices. Micro-vortex generators deeply buried in boundary layers can be used to control separation, and have demonstrated substantial improvements in high-lift L/D in wind tunnel experiments. Reduction in strength of wing-tip vortices is possible through wing-tip mounted engines, leading to reduction in drag due to lift. Efficient circulation control technologies could be developed for production of ultra-high lift, useful for SOF vehicles. Future technologies for vortex control could stem from systematic investigations into the instability mechanisms in vortices, and exciting these modes to control vortex decay.

Viscous flow control technologies are utilized to control the state or characteristics of boundary layers. Laminar flow control (LFC) via suction has recently been successfully demonstrated in flight on a section of a large transport aircraft wing. Results of this and other flight experiments demonstrate the practicality of the concept in reducing drag and improving overall airplane performance, but also highlighted the inadequacies of current LFC design methods. Synergistic use of the LFC suction system to enhance high lift performance remains to be explored. Other means of delaying transition such as heating or cooling are not nearly so advanced and warrant further investigation. Means such as suction and heating/cooling control transition via dampening linear instability waves. Research in further understanding the receptivity process of laminar boundary layers (in which external disturbances generate linear instabilities) could point the way to alternative means of transition control requiring less energy than linear wave damping. Surface mounted MEMs provide a potential means of both detecting and altering the low amplitude disturbances in the receptivity region. Riblets have demonstrated the possibility of manipulating turbulent boundary layers in order to reduce turbulent skin friction indicating further research along the lines of surface modification (including active surfaces) could be fruitful.

The general undesirability of flow separation has led aircraft designers to limit their designs to avoid the phenomenon, often eliminating or severely reducing potential nonlinear, inviscid performance levels. Active flow separation control applications have been limited to high lift and vortex lift. Advances in CFD, smart materials, and sensors can enable effective and efficient active and passive mechanisms for separation control. Applications could include increased leading edge thrust, enablement of favorable wave drag reduction concepts, stable and efficient observable-driven designs, bleedless inlet boundary layer control, and many others. Mechanisms to be explored include passive porosity, micro-vortex generators, suction, surface mounted activators, etc.

3.1.4 Aerodynamic Design Methods

Aerodynamic design methods have made some strides in recent decades with the development of CFD. Inviscid CFD flowfield analysis techniques (techniques that predict the flow past or through a given configuration) are very mature and widely used in industry. Inviscid design techniques (techniques that derive the aerodynamic lines to meet specified design requirements) have also been developed and are beginning to see use. Viscous flow analysis tools are also

beginning to see industrial use, but inadequate physical modeling and algorithmic deficiencies make them unreliable and expensive to use. Industrial use of these tools is generally limited to trend prediction. Viscous design techniques are embryonic. Both inviscid and viscous analysis techniques generally have deficiencies at hypersonic Mach numbers due to the greater sensitivity of hypersonic aircraft to accurate prediction of transition and turbulence and the complicating effects of real-gas flows. The coupling of aerodynamic analysis tools with other disciplinary analysis tools to create multidisciplinary design codes is developing and is discussed in Section 3.6.1. Wind tunnel test technique development has been largely ignored over this same period. The major advancements have been in flowfield measurement techniques and cryogenic testing technology, but both of these techniques are expensive and difficult to use. In hypersonics the introduction of flow-state-sensitive coatings has greatly improved testing capability and efficiency, and this concept is under development for lower Mach number testing. Integration of computational analysis/design techniques with wind tunnel testing is in its infancy.

The greatest gain to be made in CFD will be the development of reliable viscous flow tools capable of predicting aerodynamic forces, moments, and loads within uncertainty values and costs acceptable to the designer. The major obstacle to this capability is the ability to model the relevant viscous flow physics, particularly transition and turbulence. Much of this shortfall can be traced to a poor understanding of the physics of these phenomena. Thus a concerted effort is required to develop physical models capable of predicting these flows to within the required uncertainty (Section 3.1.5). It is also critical that these models be developed and tested sufficiently such that their limits of applicability and error tolerances are specified. Once improved physical models begin to become available algorithm development could proceed with focus on solution of the differential equation system being solved. The combination of reliable, efficient algorithms for solving the mathematical models of transitional and/or turbulent viscous flow of known accuracy would provide the aerodynamic design engineer with tools to explore innovative designs which manipulate viscous flow phenomena to aerodynamic advantage (or minimize disadvantageous effects) and can support an industrial design process. Coupling of these advanced techniques into multidisciplinary design systems would be the final step in the development of industrial CFD.

The development of viscous CFD can be compared to the state of inviscid CFD technology development in the early 1970's with the exception that the inviscid physics was well known at that time. Maturation of the inviscid technology took twenty years of concerted national effort. Thus it is not unreasonable to predict at least another twenty years to mature viscous CFD given the downsizing of the national research infrastructure and the poor understanding of the physics of these flows. The development of this CFD capability could become the pacing technology in the application of advanced viscous flow control technologies and the development of configurations that take synergistic advantage of viscous and inviscid phenomena.

This potential long development time for reliable viscous CFD methods highlights the need for interim techniques to reduce the uncertainty of Reynolds number scaling. The combination of existing or soon to be developed CFD methods with the enhanced Reynolds number capability offered by cryogenic wind tunnels provides the basis for developing such interim tools. Research into developing improved Reynolds number scaling techniques will be crucially dependent on flight experiments for quantification of uncertainties. This is highest payoff research opportunity available in the area of aerodynamic design methods.

Wind tunnel test techniques require improvement from several perspectives. For testing to directly support the design and development process, modern computational and measurement technology can be used to improve the speed of acquisition and accuracy of conventional force, moment, and load data. Pressure and temperature sensitive coatings on models that can provide quantitative surface distributions of these quantities with known uncertainty coupled with force measurements can lead to a capability to measure forces, moments, and loads simultaneously, dramatically improving the productivity of the testing process. Direct coupling of data from wind tunnel measurement and computational prediction can increase the value of both types of data to the design engineer. Incorporation of uncertainty analysis into the analysis of all test data would aid in the interpretation of the data. Better understanding of, and correction for, wind tunnel effects (Reynolds number, stream turbulence, wall and sting effects, etc.) are critical to reducing the uncertainty of the data and improving the scaling of tunnel data to the flight condition. Utilization of networking technology could make remote wind tunnel testing feasible, reducing the cost of testing. Potential model technology improvements include the use of stereolithography and other advanced manufacturing techniques to reduce the time and cost of model development. New materials for models should make it possible to test complex configurations such as high-lift configurations at higher dynamic pressures, thereby increasing test Reynolds number. Magnetic suspension could also be a means of reducing aeroelastic effects in testing of complex configurations. There are numerous additional opportunities available for improvement of test techniques. A coordinated national effort is required to bring them into practical use. Advantages will be improved designs through more accurate data with known uncertainty acquired at reduced cost in shorter time.

For hypersonic flows the picture described in the above is complicated by real-gas effects. The effects of flow dissociation on transition and turbulence is largely unknown, and wind tunnels which can isolate these effects do not exist. In recent years, quiet hypersonic wind tunnels have been developed which can produce transition in the tunnel unaffected by tunnel noise. These tunnels only exist for perfect gas flows, although it is possible to use these tunnels to simulate real-gas effects due to ratio of specific heat changes via altering the test medium. Quiet, dissociating flow facilities do not exist nor has a concept for such a facility been developed. Thus, developing an experimental understanding or databases to support theoretical prediction of real-gas, boundary layer physics must rely on flight experimentation. The ability to measure boundary layer phenomena in flight is in its infancy, but should become possible over the next 10 to 20 years. In the absence of such an experimental capability, error uncertainties for real-gas aerodynamic predictions will remain higher than the perfect gas regime. Since hypersonic vehicles are far more sensitive to design uncertainty than lower speed vehicles, investment in real-gas, boundary layer experimental and theoretical developments is critical to this class of vehicles.

3.1.5 Basic Physics

As indicated above, aerodynamics is plagued by a number of poorly understood physical phenomena which have a significant impact on vehicle design. This has forced designers to try to minimize or eliminate these phenomena in the flowfields around their vehicles, often limiting performance potential. The primary poorly understood phenomena are transition, turbulence, and real-gas effects. It is this limited state of understanding and the ability to simulate the phenomena in design testing that today renders the accuracy of the aerodynamic design process

unquantifiable, and has led to actual flight performance different from the intended design performance as on the C-17. The goal of basic physics research is to develop means by which the effects of these phenomena can be accounted for or favorably exploited in the design process.

Testing technology to support research in improved physical model development is of an entirely different character than design and development testing. Experimentation here involves measurement of time dependent flow field data, at least within the boundary layer, and complete flowfield mapping using temporally averaged data. Techniques for making such measurements have been developing for low speed flows, and some of these techniques have been applied at supersonic and hypersonic Mach numbers. The state of the art today is such that the higher the Mach number the more difficult it is to both isolate the phenomenon of interest and accurately measure the required data. Since it is well known that the development and validation of reliable theoretical models (the basis of computational design tools) requires experimental data, experimental flowfield measurement capability will be the pacing item in this area. Thus, the investment in physical model development must be strategically coupled to the investment in experimental capability. The experimental capability investment strategy must include both measurement and data analysis technologies as well as investment in experimental facilities such as quiet wind tunnels that can simulate and/or isolate the required phenomena.

Theoretical approaches to model development have been aided in recent years by the advent of Direct Numerical Simulation (DNS). DNS allows for computational simulation and isolation of flow phenomena such as transition and turbulence, but for a limited range of flow parameters such as Reynolds number and Mach number and at very high expense (a typical simulation can easily use $1M in supercomputer time). The data produced by these computational experiments is, on the other hand, highly detailed and unsteady. These data have been used to give flow modelers a different perspective on the physics and are highly complimentary to experimental data. Computational Chemistry (CC) can provide accurate, once-and-for-all predictions of reaction rate data for the chemical reactions associated with real-gas effects; gaseous reactions, gas-surface reactions, and surface catalysis.

The flow modeler thus has available data from experimentation, DNS, and CC to develop more accurate physical models, but such model development today is largely an art and is highly empirical in nature. Systematic means of developing turbulence models are beginning to emerge, such as renormalization group theory, and further development of these approaches must be stressed in the future to increase the pace of model development. Transition modeling to date has stressed use of linear stability theory and highly sophisticated, mature means of predicting transition are available. These techniques are based on the assumption that the linear instability mechanisms have been excited by some unknown means and hence they cannot account for the effect of disturbances to the boundary layer by the external environment (e.g., atmospheric disturbances, engine noise, surface roughness, and structural vibration). Future development of transition prediction must be based on absolute boundary layer disturbance amplitude growth to bring external disturbance environment effects into the models. Inclusion of real-gas effects is largely based on inclusion of physical chemistry models of the relevant reactions into the overall flow models. Accurate knowledge of these reactions is required to improve prediction accuracy, and data from laboratory experimentation and CC can provide this information.

The most difficult challenge facing the flow modeler is combining the effects of multiple phenomena (e.g., turbulence modeling for real-gas flows). These separate phenomena are nonlinear in nature and their models must be incorporated into an overall nonlinear mathematical model. Thus, developing models for isolated phenomena and then combining them is not possible. Experimental means for exploring the coupling between such phenomena is not possible today and no means of doing so have been proposed. It is possible, on the other hand, to envision experimental means of measuring combined phenomena. Thus, the modelers must develop special models for these combined phenomena barring a breakthrough.

3.1.6 Potential Aerodynamic Breakthroughs

The most significant potential breakthrough in configuration aerodynamics for cruise aircraft is the systematic reduction of drag. Currently, the largest single source of drag is friction drag during cruising flight. Laminar flow control and turbulent drag reduction technologies can cut this component of drag by a factor of two. Once this is accomplished, the largest component of drag becomes drag due to lift. Advanced configuration concepts such as those discussed in Section 3.1.2 can significantly reduce this drag component. It is this combination of technologies that can over double the L/D of large transport aircraft.

Flow control technologies represent the second potential aerodynamic breakthrough. These technologies can lead to "designer aerodynamics", i.e., highly tailored flows that accomplish exactly what the designer wants. These technologies could change the entire aerodynamics design paradigm from the current view of understanding what the flow wants to do and working with it to a future approach of deciding exactly what the designer wants the flow to do and then controlling it in a way to do it. As the various physical processes that control transition, turbulence, vortices, separation, and other flow phenomena become better understood and predictable, it will become possible to invent means to interfere with these processes to the designer's advantage. Many fluid flow phenomena are initiated or terminated by instability processes, and interference with this instability (either excitation or damping) can lead to low energy means of producing large changes in the flow. MEMs can potentially provide a means of measuring these instabilities at their earliest stages and the means to interfere with these instabilities as well. Laser energy can also be used to interfere with instabilities and surface mounted laser diodes can also potentially be used for flow control. Basic research in the physics of flow instabilities and microscopic interference technologies has very high potential leverage on the field of aerodynamic design.

3.1.7 Summary

The discussion above demonstrates that aerodynamics remains a field with significant technological opportunity. The following suggestions are made to make these opportunities available to the Air Force:

- Initiate a strong program of research and technology development in advanced aerodynamic configurations in a multidisciplinary fashion.
- Support a vigorous program of research in flow control, aerodynamic design methods, and basic aerodynamic physics driven by the requirements of the advanced configuration program.

3.2 Airbreathing Propulsion

3.2.1 Introduction

Airbreathing propulsion paces the progress of aircraft performance. This has been true throughout the history of aviation and will remain true in the foreseeable future. It is certainly the case for the advanced air vehicle concepts identified in this study, which require a wide range of types and sizes of propulsion devices.

It is interesting to pause to reflect on the original von Karman "New Horizons" report, in which he described and classified the spectrum of airbreathing propulsion cycles. These have all been pursued in the intervening time and his expectations largely met, especially for turbojet, turbofan, and turboprop/turboshaft engines, which have permanently altered the shape of civilization. Nevertheless, his hopes for the ramjet, which he viewed as the simple and natural way to propel aircraft at supersonic speeds, have not been fully realized. His vision will endure into the future, as the following descriptions of promising airbreathing technology advances will attest.

3.2.2 Turbine Engines

The most fully developed airbreathing propulsion device is the turbine engine in the form of the turbojet, turbofan, and turboprop/turboshaft. Enormous increases in absolute thrust, thrust-to-weight, specific thrust, operability, durability, response, and safety, along with enormous decreases in specific fuel consumption have been made over the past fifty years. During this same time period, entirely new restrictions on unwanted acoustic and chemical emissions and IR and RF observability have been met.

The impact of the turbine engine on overall aircraft capability is enormous. The engine plus fuel weight is between 40-60% of the vehicle takeoff gross weight across the entire spectrum of fighters/bombers/transports (Figure 3.2.1). Therefore, improvement in propulsion has a significant favorable impact on systems and plays a critical role in the maintenance of US military and commercial superiority. Consequently, the USAF has continuously funded basic research, exploratory development, and advanced development programs in order to further the advance of jet engine technology. The Integrated High Performance Turbine Engine Program (IHPTET) is the latest in the genealogy of USAF advanced development programs.

IHPTET is a joint USAF, USN, USA, ARPA, NASA, and industry program focused on developing turbine engine technologies for more affordable, more robust, higher performance turbine engines in the future. The IHPTET plan is divided into three time phases and simultaneously addresses three major types of engines: turbojet/turbofan, turboprop/turboshaft, and expendable. This phased approach allows continuous transfer of IHPTET accomplishments to the military and commercial sectors. For each class of engine and each phase of the IHPTET program, there are top level goals for the demonstrator engines. These goals provide focus for all military funded exploratory and advanced development programs, provide focus for industry investments, and serve as metrics against which progress is measured. IHPTET's three phases culminate in 1991, 1997, and 2003. Phase I is complete and has achieved its goals. Phase II is underway and significant progress has been made.

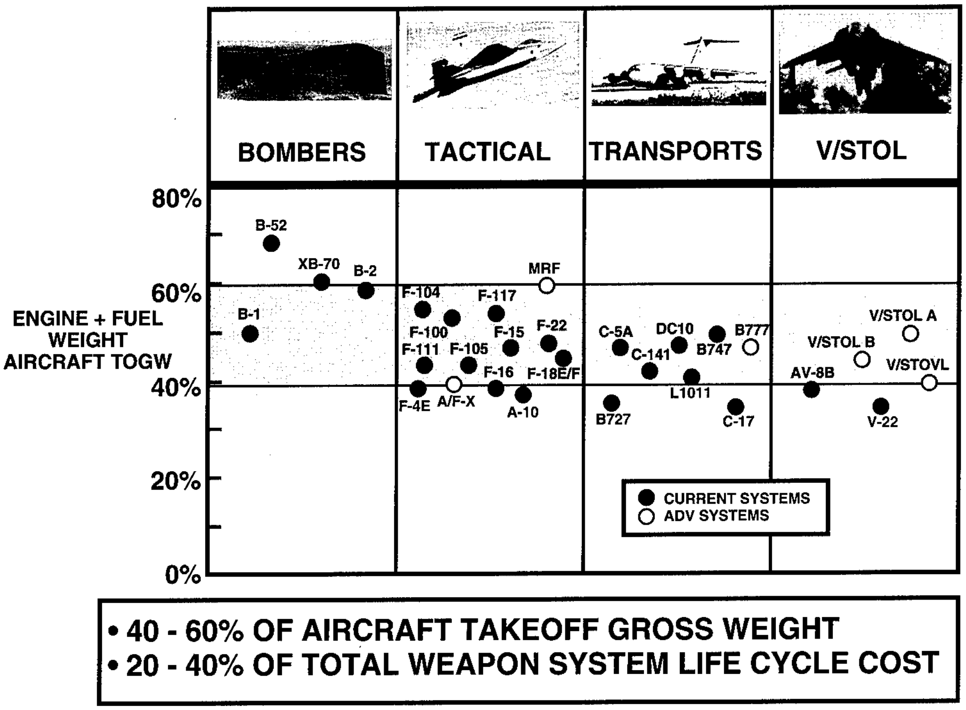


Figure 3.2.1 Impact of Turbine Engine Technology on Aircraft TOGW

The aircraft system benefits made possible by IHPTET depend on the Phase and the specific application. The results of a number of typical payoff studies are summarized in Figure 3.2.2.

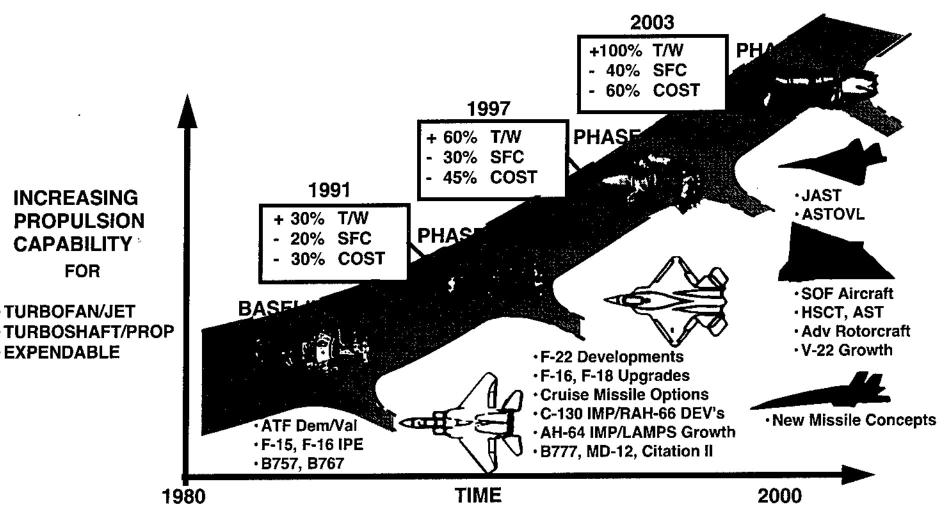


Figure 3.2.2 Weapon Systems Benefits of IHPTET Versus Time and Phase

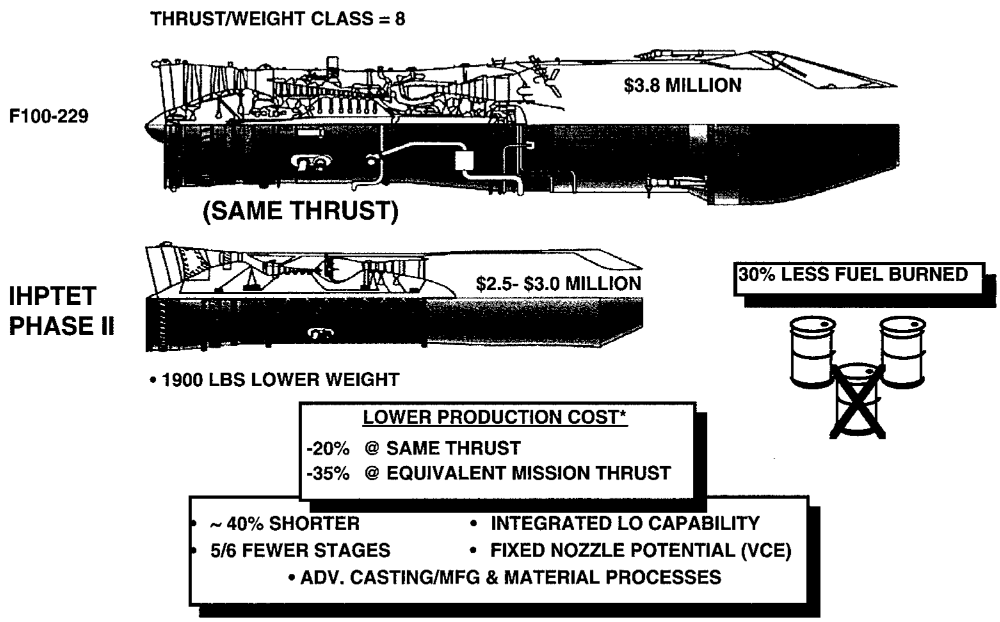


Figure 3.2.3 Propulsion System Benefits of IHPTET Phase II

The propulsion system benefits of decreased size and cost, and increased simplicity are illustrated in Figure 3.2.3.

Finally, the specific vehicle size and life cycle cost impact on a future ASTOVL fighter are shown in Figure 3.2.4.

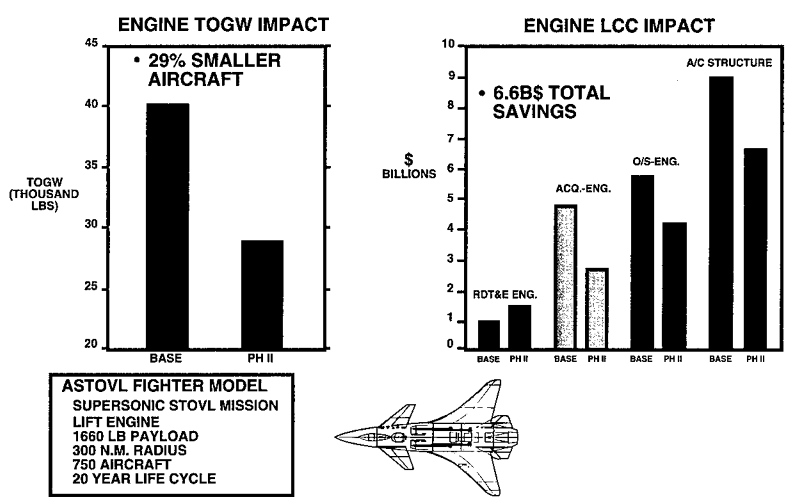


Figure 3.2.4 ASTOVL Fighter Benefits of IHPTET Phase II

The Variable Cycle Engine (VCE) is a revolutionary concept that provides significant performance, affordability, and low observability improvements. The basic advantage of the VCE is its ability to vary fan bypass ratio, turbine nozzle area, and internal cooling flows. The VCE therefore provides the ability to optimize the engine cycle for different mission requirements (i.e., range, endurance, combat maneuvering, powered lift, damage compensation, etc.)

A VCE based on IHPTET Phase II technology can provide specific thrust levels similar to those of the afterburning F100-PW-229 and F110-GE-129 but without afterburning. Consequently, the afterburner, one of the primary components of the engine, can be eliminated altogether. This will also significantly reduce fuel consumption at high power, as well as hot products of combustion that are easily detected.

The VCE offers the potential for high augmented thrust with a constant area exhaust nozzle, rather than the traditional complex, heavy, and expensive variable area nozzles. This can reduce the initial weight and cost of the exhaust nozzle by 50%, cut maintenance costs, and help signature reduction because the fixed geometry nozzle is more easily integrated into the vehicle.

The VCE is a major part of the IHPTET Phase II program. VCE technologies under development build on the VCE experience gained previously during the GE F120 engine program. New features such as the split flow core driven fan stage and the controlled area turbine will dramatically increase cycle variability.

Beyond IHPTET

Long range planning activities indicate tremendous opportunities to further improve gas turbine engine performance, affordability, robustness, and environmental emissions after Phase III of IHPTET is complete. Whereas the primary emphasis in IHPTET is to increase engine thrust-to-weight, the future will bring similar emphasis on reducing engine specific fuel consumption. Combining all these advances will lead to extreme unrefueled vehicle ranges for all classes of aircraft.

Many technologies must be simultaneously improved in order to make this possible. Compression ratios as high as 100 and fan bypass ratios as high as 30 may be required. High turbine inlet temperatures will be needed to provide the power required by the compressor and fan. The high compression will create small flowpath dimensions, making precise clearance control a necessity. Robustness will be enhanced by, for example, active structures that reduce high cycle fatigue stresses, magnetic bearings that compensate for out-of-balance effects, and active clearance control that minimizes rubs. Environmental emissions will be reduced by novel combustors designed with modern CFD models. The integral starter/generator enables the application of the more electric aircraft concept (Section 3.5.2). Sophisticated digital electronic controls will direct many features of the engine. Figure 3.2.5 is a conceptual drawing that portrays these thoughts and others.

The same technologies can be used for many military aircraft, including fighters, bombers, and transports. Since they have such direct application to transports, they enable an unusually large opportunity for the development of dual-use engines which are mutually beneficial to

the military and industry. In particular, they have the potential to provide global range, heavy lift transports (12,000 NM), long range, supersonic strike aircraft/bombers (1.5 M cruise, 5000 NM radius), and long range fighters (2.0 M cruise, 1200 NM radius).

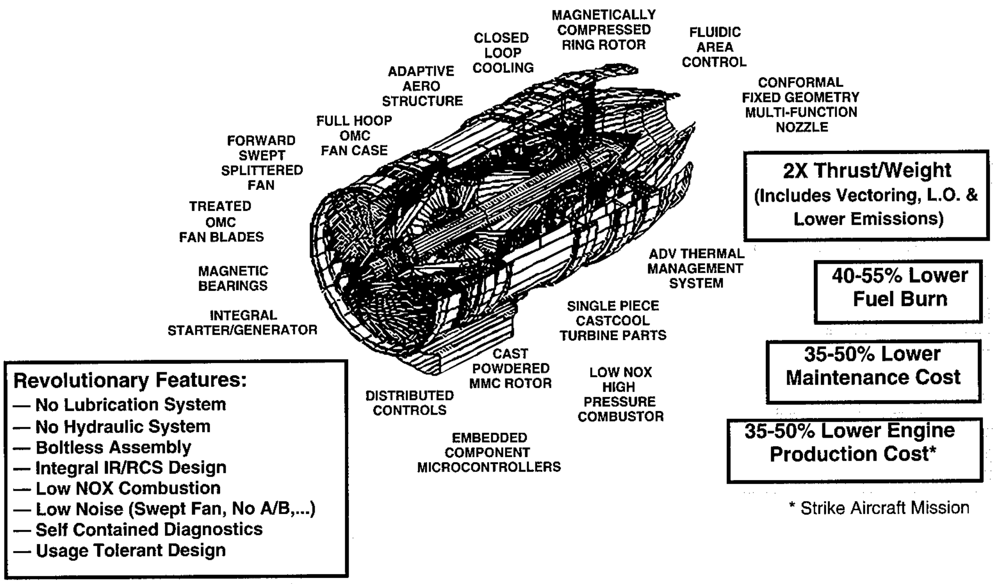


Figure 3.2.5 Emerging Advanced Engine Concepts and Potential Propulsion System Benefits

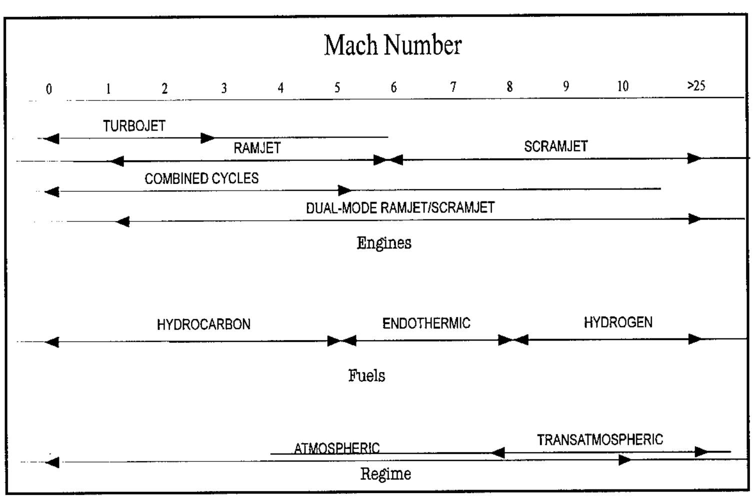


Figure 3.2.6 Airbreathing Propulsion Cycles as Functions of Mach Number

3.2.3 Hypersonic Airbreathing Propulsion

Airbreathing propulsion is possible for an extremely wide range of Mach numbers, from static to Mach numbers approaching those required for low earth orbit (M~25), as illustrated in Figure 3.2.6. The requirements for a spectrum of airbreathing propulsion devices that make possible a number of desirable hypersonic vehicles was documented in Section 2.3. Considerable progress towards practical designs for several types of cycles was made during the NASP program, but none of the efforts have entirely reached fruition and much work remains to be done. The following material describes the areas needing the most attention.

Combined Cycle Engines (0 < M < 5)

Combined cycle engines include turboramjet and ducted rocket types, as well as many combinations and permutations thereof, and are capable of accelerating the vehicle from a standing start to a high supersonic Mach number without other assistance. They received very little attention during the NASP program despite the fact that they provide the capability for both supersonic acceleration as well as high Mach number sustained cruise. They could, in fact, power many types of cruise vehicles or the first stage of a two-stage-to-orbit (TSTO) vehicle by themselves.

Several ingenious combined cycle engine configurations have recently been invented and have attracted support from the USAF and NASA, the latter being the lead US government agency in this arena. An example of these is the Air Core Enhanced Turbo Ramjet, a novel device that recaptures waste heat for use in the propulsion cycle. The IHPTET program also made many contributions to turbomachinery, materials, and combustors that benefit the development of combined cycle engines.

The greatest challenges for the combined cycle engine are in the areas of structures and materials, particularly at the highest flight Mach numbers where aerodynamic heating is greatest. Significant advancements in materials selected during the NASP program must be characterized for cruise operations and hydrocarbon fuel compatibility. Large scale hot structures and actively cooled structures for airframes and engines must be developed, and the manufacturing processes to produce them established.

It may be necessary to provide thrust augmentation at transonic speeds because the aerodynamic drag is near its peak. This could come, for example, from a separate rocket engine or external burning along the rear surfaces of the vehicle.

Dual-Mode Ramjet/Scramjet Engines (1 < M < 20)

Ramjets and supersonic combustion ramjets (scramjets) use deceleration of the oncoming airstream instead of rotating machinery to compress the flow. They are therefore simple in the sense that they have no constantly moving parts, although they must endure extraordinarily harsh environmental conditions. The dual-mode ramjet/scramjet allows continuous transition from ramjet to scramjet operation by using thermal choking (i.e., the apparent blockage caused by the addition of heat) in place of mechanical variation of the exhaust nozzle throat area. This further simplifies the engine and enables a single duct to provide thrust over an extremely wide range of flight Mach numbers.

Several important challenges remain before practical dual-mode ramjet/scramjets are available. They include: (1) high temperature structures and materials issues similar to those of the turboramjet, but without the presence of rotating machinery in the flowpath; (2) the development of short, efficient, stable, durable combustors, particularly when liquid hydrocarbons or endothermic liquid hydrocarbons are the fuel; (3) demonstration of smooth ramjet/scramjet mode transition, forward and reverse; (4) demonstration of the required levels of performance and operability over the relevant flight Mach number range; and (5) development of techniques to properly integrate the pitching moments of these engines, which can dominate the aerodynamic moments, into the flight control system.

A special concern is the determination of the maximum Mach number at which scramjets can reasonably be expected to provide adequate thrust. For several natural reasons, the thrust of a scramjet declines rapidly beyond a flight Mach number of about 12 and eventually passes through zero at a flight Mach number estimated to be in the vicinity of 20. It is therefore crucial that work be carried out in the near future to pin down the very high speed behavior of scramjets and to explore what can be done to extend the range of satisfactory performance.

The Ram Accelerator

The ram accelerator is a device for accelerating small vehicles that may be thought of as a ramjet in a tube. The projectile is injected into a tube containing a combustible mixture of gases at a supersonic speed sufficiently high that the leading edge shock wave system causes the mixture to react. This generates forward thrust just as in a ramjet or scramjet, and the vehicle will continue to accelerate. Since the chemical reactions take place within the shock wave system, the "combustor" is quite short.

The ram accelerator can simply and inexpensively bring projectiles to hypersonic speeds, and has demonstrated this capability up to about a Mach number of 5. It can form the basis either for the development of a devastating weapon or for the ground test simulation of hypersonic flight. It is one more member of the airbreathing propulsion family that should be considered for future applications.

3.2.4 Summary

As Dr. von Karman knew, airbreathing propulsion is a primary enabling technology for almost every type of aircraft. This is especially true for vehicles that must be capable of sustained cruise in the atmosphere.

The Air Force S&T community is well aware of these facts and has continuously made thoughtful, fruitful investments in the future of airbreathing propulsion. This has made the US the outright world leader in aircraft propulsion and has paid handsome dividends to our military and economic security.

We **strongly** believe that this has been the correct course of action, that it should be continued, and, in particular, recommend the following:

- The IHPTET program be completed as planned, and that any redirection be done only after the long term benefits of the program have been carefully considered.

- Planning for the Beyond IHPTET program proceed vigorously now so that the most advantageous airbreathing propulsion opportunities will be exploited in the future.
- Combined cycle turboramjet development be continued until it is available for practical application.
- A deliberate program for exploration and solution of the key dual-mode ramjet/scramjet problems be devised and implemented.
- Innovative airbreathing propulsion concepts, such as external burning and the ram accelerator, continue to be pursued.

3.3 Structures

3.3.1 Introduction

Structures technology encompasses an extremely wide range of component technologies from materials development to analysis, design, and production. This section will discuss overarching developments that are likely to produce more efficient, affordable aircraft during the next 25 years.

The structure of a fighter or attack aircraft comprises about 25-35% of its take-off gross weight (the figure is closer to 35% if we consider the "clean" take-off gross weight). This contrasts with 15-20% devoted to engine weight and another 10-15% in equipment weight (such as avionics, air-conditioning and anti-icing systems). Fuel adds around 30%, depending upon the range. The structural weight fraction of attack and fighter vehicles has remained fairly constant over the past 30 years, not because of lack of structural technology progress, but because of increased system performance requirements such as stealth.

During the past 30 years, maturation of the finite element structural analysis method and the development of advanced composite materials have improved aircraft structural performance, reduced risk (because of more accurate prediction before testing), and shortened development time. New structural technology improvements have not only blunted the increased costs that accompany demands for increased performance, but have also supported new design forms such as the X-29 forward swept wing aircraft and F-117 Stealth aircraft.

No single area in the disciplinary ensemble of structures technology is expected to be a breakthrough area in the foreseeable future, although steady progress in all areas will improve airframe efficiency. Continued development of new computational methods, improved materials, better manufacturing methods, computer aided design (in which "trades" or "what if" questions can be reliably assessed), and development of onboard structural "health monitoring" will combine to add substantial value to structures technology. This will allow us either to hold the line on costs or reduce cost of systems while improving effectiveness.

The following sections will focus on developments in future aircraft and engine design that will improve both aircraft and engine performance, advance the technology exploitation process, and reduce life cycle cost. These are

- tailored structures and engineered materials for airframes and engines,
- active control of stiffness, including adaptive smart structures and flow control, and
- self-diagnostic structures, including structural health monitoring.

3.3.2 Background and Scope

The necessary steps to translate science into engineering have been described simply as understanding, measurement/computation, control, and exploitation. The exploitation of science is a concern of weapons system development. The linkage between materials, structures, and production in the structures technology exploitation scheme has been described by several sources as a linked process as shown in Figure 3.3.1.

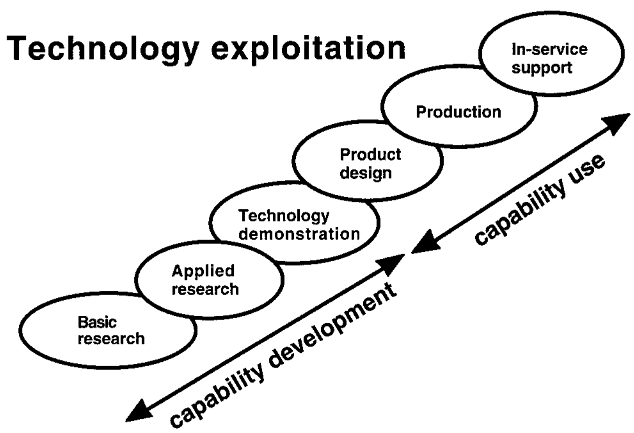


Figure 3.3.1 Necessary Links in the Chain of Cost Effective Technology Exploitation

While the first part of the technology exploitation process currently consumes only about 10-20% of the total product development budget, costs beyond this stage depend heavily upon this initial part of the chain of events. The processes shown in Figure 3.3.1 appear as part of a long chain, but, in reality, they are interconnected and must be integrated.

Strengthening the linkages in the technology exploitation process must improve to meet competitive demands throughout the world. Structures technology development requires good materials research. This research includes not only theoretical aspects such as failure theories, but also includes generation of experimental data such as fatigue data. The technology demonstration portion is equally important because the total cost of the product can be reduced by drawing on the experience gained by building small technology prototypes or demonstrators.

Basic research is funded heavily by government agencies at the university level and in government laboratories. Unfortunately, basic researchers can work in isolation (with constricted feed-forward and feedback to and from the applied research and technology demonstration areas). The results of their research, when measured by academic standards, may be exemplary. But basic research, unless it is purely philanthropic, requires strong industry feed

back and what has been described as "market focus." Communication among the diverse participants in the technology process - university, industrial, and governmental - can be a major problem. These problems include

- changing commercial priorities and leadership,
- differences between academic and commercial cultures, and
- differences in the definitions of success.

Small scale funding for research from organizations such as AFOSR allows a mix of "players" and the opportunity to fund "curiosity driven" high quality research that demonstrably benefits technology at the basic and applied research levels. Research programs that ignore the vital feedback link between science and technology will be less productive for the Air Force, just as they are less productive for companies.

The following sections discuss some research areas likely to have an effect on the "capability development" portion of the technology chain. These developments will influence aircraft produced early in the next century and their effectiveness, both as a weapons system and as a cost effective component of Global Reach and Global Power.

3.3.3 Tailored Structures and Engineered Materials

The development of new materials, materials processing, and manufacturing processes (including fabrication, joining and finishing) has a profound effect on the cost and effectiveness of the aircraft design that goes beyond reducing aircraft weight. The choice of materials affects all links in the chain shown in Figure 3.3.1. Some types of materials are costly, but their low weight or their superior thermal properties may be necessary to the design so that high manufacturing and in-service maintenance costs must be accepted. Complicated trade-offs between weight/performance, manufacturing, and maintenance can be addressed at the materials level by combining materials to attempt to capture their best properties and minimize their limitations. This is done by fabricating or designing engineered materials.

"Engineered materials" are combinations of materials, either in solution (such as an alloy) or distinct (such as filamentary graphite/epoxy) specially designed to take advantage of superior features of its components. For instance, advanced composites contain light weight materials such as carbon, which are brittle, but which have been processed so that the density of flaws that could lead to failures is small. A matrix of relatively weaker material such as a resin or even a metal is used as a binder to hold the fibrous material together and act as a load transfer mechanism.

Advanced composite structures are one of several so-called "engineered materials" that have appeared during the past 25 years. Advanced composite materials have high strength-to-weight and high stiffness-to-weight ratios. On this basis alone, their use can reduce the weight of structural members, joints, and fittings. However, because these materials are mixtures of constituents, their failure modes are different than conventional metallic materials. Continued basic research is needed to understand and control these failure modes.

Advanced composites are both a material and a micro-structure, designed for optimal load path resistance. This capability to design load paths at the micro level is as important as the material's low weight. The X-29 research aircraft was the first to orient or "tailor" advanced

composite directional strength and stiffness to prevent wing aeroelastic divergence and adverse interaction between the wing bending and aircraft flight mechanics modes. This so-called "aeroelastic tailoring" is a major advantage of advanced composites wing and tail structures. Less advanced composite materials such as fiberglass/epoxy have been used in small kit-built airplanes because of the ability to fabricate low cost, smooth, strong airframes.

Other engineered materials include advanced alloys used in high temperature turbine blades. These materials are solutions of different elements, each of which brings a superior performance attribute to the material system. Other engineered materials may have a thin coating deposited or engineered onto the blade surface to resist surface abrasion and wear or to provide thermal properties unavailable from a single material. The materials are the result of extensive "cut-and-try" research.

Attachments and fittings add substantial weight to the structural elements that they connect. One solution to reducing the weight of joints and fittings is to produce "graded" structures that begin as one material and end as another. A biological example of a graded structure is a tendon that begins as a bone material, becomes a tendon, and then continuously progresses to become muscle attached to other muscles. Engineered materials can increase attachment efficiency and reduce the number of fasteners. This potential for reduced part count, together with smaller, integrated joints and fittings, makes engineered materials important elements of future aircraft structures.

Deposition schemes can now construct a coating that is only a few atoms thick. This layer is virtually free of defects so that its strength approaches atomic bond strength, making it an ideal candidate for turbine blades and other uses where corrosion or other surface effects are critical to the life of the part.

The trends toward multi-functional demands for materials and devices leads us naturally to a structural system that begins to resemble a biological form. Biological processes are a useful map for the future integration of load bearing materials and non-load bearing materials such as electronic or low observable materials. Biological process still can make some materials, such as nacre in mollusk shells, far stronger that we can reproduce it in the laboratory.

In the future, advanced composite technology will focus on cost effective applications for vehicle production. Advances in aircraft design, particularly in the area of uninhabited vehicles and modular vehicles, will lead to more efficient aircraft with new aerodynamic shapes. New materials and materials processes will contribute to increases in aerodynamic efficiency, manufacturing efficiency, and ease of maintenance.

3.3.4 Adaptive and Smart Structures

Aircraft structures have diverse, conflicting mission requirements. For instance, landing and cruise requirements are in conflict so landing flaps are added to increase the lift at low speeds and then designed to retract at high speeds. Demands for both low speed and high speed combat performance can be addressed with variable sweep wings, although structural weight must be added to provide a wing pivot. These aircraft are adaptive machines.

Adaptive aircraft of the future may have the capability to survive battle damage and still retain substantial combat effectiveness. Such an aircraft structure needs sensors to provide

information and feedback from the structure and controllers to compensate for the damage. Limiting the effects of battle damage and controlling overload conditions can be provided by aerodynamic surfaces such as ailerons powered by hydraulic actuators.

Active aerodynamic control is also an alternative to adding mass to an aircraft structure to increase flutter speeds. This feedback control scheme is one in which surfaces such as an aileron are used to generate dynamic loads to suppress unstable oscillations. The ability to suppress flutter has been demonstrated repeatedly over the past 20 years and so it is not new technology, although it has not been used extensively. Active load control or stiffness control can be a valuable addition to new vehicles with a wide range of mission requirements and configurations. These vehicles include HALE aircraft and small uninhabited aircraft.

Another way to control loads without articulated aerodynamic surfaces is to use self-straining actuators embedded within the structure. These actuators, usually piezoelectric devices or shape memory alloys, attempt to expand or contract on command. This expansion, controlled by an electric field or by heat input and resisted by the rest of the structure, will create a change in shape of the active wing element. This change in shape will, in turn, change the aerodynamic load on the wing or lifting surface. With feedback control, the wing flutter speed will increase and the surface can be used to maneuver the aircraft. The result is called a "smart" structure.

The term "smart structures" most often refers to any structure with embedded sensors, electronics, and actuators. The maturity of most smart structures technology for active control is 20 years into the future because of material reliability concerns, current lack of ability of the materials to change their shape to create sufficient surface shape change, and lack of a mission.

The most likely candidates for smart material load control are very flexible surfaces such as the HALE aircraft or smaller surfaces such as missile fins. Available piezoelectric materials cannot withstand harsh environments, nor are they expansive enough to deform large aerodynamic surfaces. A related problem for aeroelastic load control is the unavailability of anisotropic actuators to independently control bending and torsional response.

3.3.5 Hot Structures

Hot structures have played an important role in the development of many different airframe and engine thermal structure concepts over the years. In the harsh engine environments, superalloy and titanium alloy structural concepts are common-place. Even in the airframe environment, over thirty years of hot structure experience have been accumulated. Typical of these airframe concepts were certain X-20 components, the B-58, and many missile fin designs. More recently, hot structure designs were advanced by the National Aero-Space Plane (NASP) Program. Key developments in this program included titanium, titanium matrix composite, and refractory composite hot structure concepts. Tremendous progress was made in understanding the material response and in developing fabrication techniques. Several full scale structural components were completed. Unfortunately, the demise of the NASP program left much of the verification undone.

Despite the demise of the NASP program, the requirement for hot structures continues to increase. The advantages and payoffs of hot structures are recognized as enabling for the challenges of operating in the high speed flight regime. Advanced systems as divergent as a

single use hypersonic weapon and a fully reusable transatmospheric vehicle will not be feasible in the future without the advances in the durability, weight, and cost of hot structures.

Hypersonic weapons can provide the standoff ranges and speeds that assure greater system survivability to future threats. These weapons will require hot structure in both the engine and airframe. The entire airframe may be a hot structure, and hot structures will certainly be required for the nose, leading edges, and fins. If produced today these would most likely be superalloys and titanium for the body and a refractory composite for the nose, leading edges, and fins. However, tremendous advantages in weight and performance are possible through the development of advanced titanium alloy, metal matrix composite, and ceramic matrix composite hot structure. In the engine, the inlet and nozzles will feature hot structure designs as well. Ceramic matrix or refractory composite hot structures appear to be ideal. The key issue will be the affordability (primarily acquisition cost) of these advanced structural concepts when compared with today's technology levels.

Reusable vehicles such as transatmospheric vehicles, hypersonic cruisers, and hypersonic fighters are even more dependent on affordable hot structures. Again, hot structures will be required in the airframe and engines and in many of the same locations as required by hypersonic weapons. However, in addition to the weight and acquisition cost of hot structures in these vehicles, the support cost is of equal or greater importance. In addition, the durability and inspectability of the hot structure is a key factor in the development of reusable hot structure concepts. Current concepts would require frequent inspection and replacement after tens of hours of use due to a lack of durability in the thermal and acoustic environments in which they operate.

Finally, future stealth vehicles will require affordable hot structure in certain aft fuselage areas. The hot structure in these regions will have the additional requirement to be compatible with low observable design principles. Durability, weight, and cost will need to be addressed. Weight reductions in the aft fuselage area through structurally integrated airframe nozzles, while simultaneously increasing component life (hundreds to thousands of hours) will significantly enhance war-fighting capability of stealth systems.

In the systems of tomorrow, hot structures play a key enabling role. From routine flight at hypersonic speeds through advanced affordable stealth aircraft, their development is essential. Issues of weight, durability, acquisition, and support cost must be addressed for these systems to become a reality.

3.3.6 Structural Health Monitoring and Diagnostics

One important type of smart structure is related to avionics. Rather than being concerned with looking for targets, avionics can be a part of the structure to interrogate the structural components about their "health." Structural health monitoring and diagnostics move the philosophy of structural design one step closer to biological form by adding "nerves" to the aircraft system. This addition will

- increase chances of completing a mission,
- provide information to maintenance organizations, and
- provide data to logistics systems for planning.

Onboard health monitoring provides pilots with information for real-time mission planning so that they can decide to complete the mission, abort the mission, or continue with well-defined deficiencies present in the aircraft, its structure, and skin. Improvements in health monitoring could alert the pilot that structural damage, while perhaps slight, had increased the size of the radar signature just as they now measure temperatures in engines. This type of new structural information could be acquired, stored and re-acquired, either in-flight or on the ground, for retrieval by Tactical Mission Planning. The necessary components of such a system are

- sensors,
- network planning,
- processors,
- information storage and retrieval, and
- structural health control feedback.

Sensors can be embedded or attached to the structure. They must be inexpensive and very small. The network connecting the sensors to the processor must extend throughout the aircraft, but could be used by other aircraft health monitoring and diagnostic systems. Sensor technology is developing rapidly. One type of sensor being developed measures the "sounds" of crack growth. Transducers transmit acoustic signals throughout the structure and measure changes in frequency associated with crack growth at remote sites. Other sensors under development will detect and measure separation (delamination) of advanced composite material layers.

The network structure envisioned for health monitoring will most likely to be a fiber optic network designed for survivability so that it can transmit information even when one or more elements or paths is disrupted. The network must be highly reliable so that there is a high confidence level that an event has occurred and the processor output is not incorrectly identifying a fault.

The processor must receive signals and analyze an array of sensors to determine if an important event has taken place. It also measures the extent of damage and provides a diagnosis of what has happened and what could happen. Processors can be shared with non-structural health-monitoring and diagnostic systems so that they can make recommendations on the situation of the total aircraft, including weapons, avionics and observability.

Some processors with memories can be embedded in or mounted on modules to record the "name" of the module and its history. This history can include the environment, special events, and maintenance. This type of information is particularly important to define the service use of a particular aircraft and the impact of this use to service life. Processors provide recommendations to the pilot or feedback controllers that can compensate for detected damage that create operational deficiencies. Information storage is important to the maintenance and logistics support community and their planning activities. This information can help to determine the readiness of the aircraft and can even be used for "condition-based maintenance."

The development of structural health-monitoring and diagnostic systems is driven by sensor/network/processor technology as well as development of signal processing technology. The goal of high reliability, low cost (measured in thousands of dollars), and light weight (measured

in tens of pounds) appears to be achievable within the next decade. The potential impact on mission planning, maintenance, logistics and, in the end, weapons effectiveness is extremely high when compared to the cost.

3.3.7 Summary

Demands for efficiency and multi-functionality are driving the structures technology to develop new capabilities where the materials selection and the structural forms are highly complex and integrated. It is possible that the routine demand for smart skins that are combinations of aerodynamic load generators, load carrying elements, radar receivers, and emitters is not far off. Applications and technology demonstration to advance structural technology are essential parts of basic research. These application programs, referred to as 6.2 and 6.3 programs in the Air Force, are vital links in the technology exploitation chain and must be pursued.

The Air Force must coordinate its research efforts with universities, government laboratories, and industrial organizations to encompass the whole chain of product development. The major future structural research issues revolve around the integration of existing and new materials into functional systems with high quality, low cost features. Measures of quality include weight, range, operational cost, and required support facilities. Cost is measured relative to the demands made upon the system. Systems integration is more important in the materials and structures area because all components of the structure and its associated elements must work together at ever increasing levels of complexity and with increased demands for efficiency and cost reduction.

3.4 Vehicle Control

3.4.1 Introduction

This technology set centers on use of feedback control theory applied to control all air vehicle functions, especially those that are designed to be controlled dynamically during a mission. Some control is accomplished automatically, some manually by the crew, and some control (e.g., vehicle attitude in unstable regions) is a blend. Interaction of the vehicle with off-board systems will also require some degree of distributed control of that dynamic network. At the core of this set of technologies are those which deal with the problem of integrating humans into the air vehicle system. The "human system interface" is critical to this core and will be discussed here in section 3.4.3. All control and human interface technologies are relevant to uninhabited as well as inhabited vehicles.

3.4.2 Control of Flight and Mission Functions

It is clear that more functions will be and should be controlled to achieve better system/subsystem performance and/or to lower cost. "Control criteria" used by designers of air vehicle flight control laws continue to be developed and need to expand to mission critical and other functions. It is especially critical when control involves "man-in-the-loop". That specific technology need will be addressed in section 3.4.3 since vehicle and other aircraft cockpit controls need to be carefully blended with human operating capability.

State-of-the-Art in Control

Vehicle flight control involves digital fly-by-wire (FBW) with redundant hardware and software to achieve flight safety design requirements. Reconfigurable control has been demonstrated in simple (few surface failure) form. This involves new concepts of fault diagnostics and fault tolerance. Aircraft emergency recovery using engine asymmetric thrust and simulated flight control hydraulic failure has been demonstrated. Thrust vectoring for control and enhanced turning at high (even post-stall) angle-of-attack (AOA) has been demonstrated. Active control of flexible wings and for "flutter suppression" has been achieved in practice. Automated control of many mission (avionics) functions is expanding rapidly.

Trends in Control

Flight control is accomplished predominantly by non-redundant aerodynamic control surfaces which have triplex or quad redundant command signal and dual or triplex actuator power sources. However, reconfigurable control strategies which depend on control surface redundancy are expanding. Aerodynamic and structural loads are being more actively controlled locally (not just via the aircraft six degrees of freedom) to achieve better L/D performance and lighter weight, lower cost structures. Engine control is from throttle to engine-installed digital electronic controllers, which receive some information from air vehicle mission/central computers. The trend is to slowly increase the automatic control authority over engine, inlet, and nozzle functions and geometry.

Controlled functions are incorporating smart built-in test and fault diagnostic functions embedded in the on-board controllers. In-flight reconfiguration to circumvent failures is becoming more pervasive (mission availability and maintenance labor-hours are benefiting). Avionics function control is rapidly growing, but has become very complex due to the need to blend automatic versus manual functions and decision aiding. Increasing digital hardware and software capabilities are enabling the rapid growth of functions to be controlled.

The overall trend is to include central control over more functions such as subsystems (via Vehicle Management Systems). Such trends are leading to better integration of subsystems, for example, and are necessary for "more electric" airplane concepts. The trend towards integrated flight control, to include thrust vectoring and use of distributed aero control effectors, allows for designs of tailless and other new, low drag, low signature configurations.

Mission adaptive control, evaluation of solution concepts via manned simulation, reliable/maintainable distributed controls, high off-boresight systems, distributed control systems, model based control and diagnostics, and pilot-directed guidance auto-pilot mode are technology needs recognized by the Air Force Modernization Planning Process.

Forecast for Control Technologies

Mission functions and vehicles will have stability and control built in to allow carefree and unrestricted maneuvering. The systems will have fault diagnostics integrated into a fault tolerant design. Flight controls will be better integrated into the vehicle structure to take advantage of distributed aero control and/or active flexible control of structural shape and/or thrust vectoring. Redundancy will be inherent in the distributed control effectors, not requiring additional redundancy in signals to each effector. There may be some redundancy built in to proces

sors and sensors for survivability. External aerodynamic control will be achieved without use of separate hinged surfaces. Many stabilizing fins used now will be gone from all new and some modified aircraft. Engine control is fully integrated into the control architecture such that command signals feed into and sensor signals feed out of inlets, engines, and nozzles to appropriate control processors. There is more use of "fluidic" control. Air data sensing will be done with sensors (e.g., electro-optical) which look ahead into the free stream and can look far enough ahead to sense gusts and other properties (i.e., presence of CBR agents). Other air data and fluid flow sensors will be located to measure internal flows (e.g., inlets, engine components, nozzles, and exhaust). Smart skins (with embedded DC to light sensors) and smart structures (with embedded stress/strain, damage, and corrosion sensing) will be in widespread use for active control of apertures and structure, and for determining the need for maintenance. Control criteria will expand to provide design guidelines for all controlled functions. The criteria must take into account expanded levels of mental performance (Cognitive Engineering).

Control systems architecture will evolve along lines that have a human analogy: system flight and survivability critical functions will be performed by a fault tolerant, automated (subconscious) system. Mission critical functions will use a blend of automated and manual control (with ever increasing use of expert system/AI/neural network methods to simulate human decision making). Smart sensors and control actuators will have integrated embedded processors for managing their functions. They will perform all lower level tasks, freeing central processors for higher level functions while eliminating dedicated and separate control units. Active control will use intelligent adaptive processing (which includes fault diagnostic and reconfiguration ability) in order to continue a mission at maximum achievable effectiveness and to greatly reduce maintenance labor-hours and training (for diagnostics and CND false pulls). Digital semiconductor processors and "software" used for control will be replaced in increasing scales by biotechnology grown organic devices. Speed and throughput capabilities of those will pace their introduction, since they should be low cost to produce. Digital software, where used, will be fully modular and reusable. Generation of software used for feedback control functions will be fully automated and integrated into the control design process. Much of the control technology will be commercial off-the-shelf, except for that interfacing directly with enhanced performance human crews.

Austere control concepts and devices will be used in specialized form on all smart weapons, for precision airdrop, and distributed throughout the aircraft to reduce overall costs.

Control technologies will be applied to air traffic control and control of air vehicle and weapons systems in combat and training. Control technologies will enable more accurate and productive ground and flight tests. Test point data acquisition, reduction, and test parameter sequencing will be tightly and effectively controlled.

Control technologies will pervade the manufacturing process. Critical initial applications will be in control of key characteristics such as material properties.

3.4.3 Human System Interface

The human system interface involves not only the devices which convey information to and from human controllers/decision makers, but it is dependent on more intimate, exact knowledge of the human. Because of this, we offer a discussion on displays and controllers which

interface with the human and a discussion of cognitive engineering, which involves human workload and decision making. Future systems must benefit from more intimate involvement with humans, which is facilitated by the design of the vehicle itself.

Displays and Controllers

State of the Art in Displays and Controllers

Wide angle liquid crystal and helmet mounted displays are in hand. Filtering and prioritizing techniques of presenting information with "virtual" control switches on one integrated display are being developed by both the technical and human factors community. Difficulties lie in integrating crews with their information and controller interfaces, especially when the dynamic interactions can cause pilot induced oscillations (PIO's) or workload/information overload.

Trends in Displays and Controllers

The following items are technology needs recognized by the Air Force Modernization Planning Process: crew accommodation and safe escape, real-time information in the cockpit (RTIC), human centered crew station design, voice activated/holographic imaging, night vision goggle (NVG) compatible cockpit, advanced aircrew interface, common AMC aircraft cockpit and common avionics upgrade, McDonnell Douglas human modeling system, synthetic vision technologies, knowledge-based crew station displays, voice input and feedback program, situational awareness cockpit displays, helmet mounted cueing system, color cockpit night vision sensor-compatible cockpit lighting, common cockpit for tanker/transport aircraft, head up display-less (HUD-less) cockpits, integrated situational awareness flight management avionics suite, internetted visual displays for multi-crew aircraft, in-flight mission planning system, knowledge based target acquisition system, synthetic terrain imagery (STI) for helmet mounted display (HMD), and curved flightpath display format. All are concepts in the area of human systems interface which hold promise in expanding the range of options open to address the design of aircraft controls and displays.

In addition to the above listed concepts, the following trends will affect the cockpit design of new or upgraded cockpits:

- Flat panel displays are evolving in size and capability (10" x 10" is very near).
- Helmet mounted displays are evolving rapidly with increasing functionality and accuracy.
- Cockpit control devices which interface with the crew—including tactile (touch sensitive) devices near or on displays, switches, control stick (with multiple function switches), and throttle for Hands On Throttle and Stick (HOTAS) operation—will continue to evolve.

Forecasts for Displays and Controllers

By the year 2005, the aircraft pilot (or any other member of the aircrew) will have an extraordinary visual awareness of the situation of the air vehicle. The key challenge is to provide useful, accurate information, not just data for processing. Color, three-dimensional, hi-

resolution imagery and sound will be provided via helmet and helmet visor. The imagery and sound will be so realistic that differences between information provided in a cockpit in an aircraft, a cockpit in a location other than in an uninhabited aircraft, or in a cockpit simulator for training or planning would be minor, except for g-forces which often provide significant situation awareness.

Displays will evolve rapidly in the commercial sector to encompass full 3-D, stereoscopic features and allow high resolution virtual reality presentations on-board in any size needed. An extraordinary amount of information could be provided instantaneously to the pilot or operator. Realistic global, regional, tactical, geographical, environmental (natural weather and air turbulence, for example), and electronic warfare, chemical, biological, and radiological warfare environmental conditions could be presented. Stored knowledge of maps, intelligence images, mission planning, predicted mission scenarios, and flight manuals would be available in image form. Images from on-board and off-board air platform sensors would be available. Images of aircraft exteriors and interiors will be available from air vehicle, propulsion, weapon, mission sensors, cargo, and cockpit monitoring and diagnostic systems. However, due to pilots' ability to handle only about seven distinct pieces of information concurrently, the challenge is to determine which seven and when.

Via training and recording of actual missions for each pilot, individualized integration and filtering of all of this information will be incorporated into one presentation to each pilot or aircrewperson. Each presentation would be composed of reality information (information that one's eyes normally could see), enhanced reality (information from non-visual sensors), and virtual reality of animation, graphics, and alphanumerics (information that visualizes non-image data). Reality, enhanced reality, and virtual reality images of past, present, and future information of locations remote from the aircraft could be carefully presented. Extreme care must be taken to ensure that information, not raw data, is made available from on-board and off-board processors.

The pilot will be able to control the aircraft's situation (i.e., air vehicle, weapons, mission sensors, etc.) via multiple real or virtual controls in a cockpit. In addition to hand and feet controls will be head movement, eye movement, voice command sensing, brain activity, breathing, and blood pressure and rate controls. Controls and displays attached to the air vehicle crew stations would be used by more than one person — the maintenance crew would use them. The portable controls and displays attached to the flight suit and helmet would also be used during ejection, parachuting, and on the ground for search and rescue and enemy avoidance. During ejection, these controls and displays would be provided with portable power and emergency data including maps, navigation, communication, medical, survival, and repair information. Control will include those accepting human inputs through direct sensing and stimulus from and to the human brain (Cognitive Engineering).

Cockpit mounted displays will potentially evolve into back-up displays to the HMD. The HMD will be the smallest, lightest weight display and the only display which could be used during laser attack. Lightweight, inexpensive laser eye protection devices and coatings are being developed for helmet visors. When the laser protection is activated, the visor becomes opaque. Information to the crewperson can only be restored via the HMD. If the information is accurately presented on the HMD in coordinates aligned with the aircraft and the real world, no other display is needed since the display for one eye can act as back-up for the display for the

other in case of display failure. During laser attack black-outs, a virtual image of the cockpit can be generated on the HMD. With hand and finger tracking sensors, the display can generate the virtual images of the pilot's hands and fingers on the controls.

Two very important, intensive data processing functions of the displays are information selection and image selection. Individual images need to be reshaped, trimmed, enhanced, and annotated to be fused with other images into one presentation. Priority of information will be determined real-time as to which images and data are presented. Priority and location of information on the display will be automatically determined real-time. Feedback loops to directly measure crew cognition and workload saturation are routinely used to adjust display content and controller gains.

Display technology available will be miniature lightweight optics, high speed miniature avionics, automated image-processing, real time animation generation, real-time decision making, light-weight composite materials, and cockpit system integration. Human factors, vision, brain, and human control research is enhancing the development of displays.

Cognitive Engineering

As the Air Force moves into the "Information Age", either willingly or reluctantly, it is vital that the man-machine interface be understood. Without this understanding, the Air Force will not only fail to take advantage of possible gains, but also may find that "improvements" lead to deterioration of performance. It is essential that the Air Force undertake a long term research program to define the activities that people do best, what and how much information is needed for these activities, how to present this information to people so they can make the best use of it, and then describe automation to support people's needs.

The following items address issues related to cognitive engineering and are technology needs now recognized by the Air Force Modernization Planning Process: adaptive function allocation to optimize human performance, advanced human factor technologies, real-time information in the cockpit, human-centered crew station design, voice activated/holographic imaging, operators intelligent associate, advanced aircrews interface, McDonnell Douglas human modeling system, synthetic vision technologies, voice input and feedback program, systolic cellular processor, knowledge-based target assignment algorithm, and pilot-directed guidance auto-pilot mode.

Future Air Force Capability

Twenty-five years from now the air crew could have extensive information about their situation; their location, speed, direction and altitude, state of their location, and the condition of each important aircraft sub-system. The air crew's mission orders will have been prepared on timely information and can be modified while they are en route, if necessary.

Some primitive steps have been taken in this direction. Unfortunately, the usual step is to automate what can be automated and assume mission planners and air crews can cope successfully. The net result has been to automate these activities where the least human attention is needed and to increase the work load at those tasks where more human attention is needed. However, there is an increasing body of evidence that suggests well trained people can handle seven, or less, individual pieces of information at a given time and act effectively there on.

The thoughtful reader will instantly perceive that a conflict of sorts exists between a near infinite amount of data and the limited ability of the air crew to cope with all this data. If all this data is to be used to the maximum benefit of the Air Force, then the following steps are required:

- Apply accepted magnetic resonance imaging (MRI) and positron emission tomography (PET) brain scan methods to determine extent and intensity of brain activity when a person is subject to complex cognitive activities. Initially these cognitive activities should be identical with those developed at Armstrong Laboratories and used with the Subjective Workload Assessment Technique and the Subjective Workload Dominance techniques, as well as the Crew-Centered Cockpit Design Project, the Visually-Coupled Acquisition and Tracking system activities and the Virtual Reality/Super Cockpit Research. The goal is to begin to establish quantitative measures for these activities. It is from this foundation that future research will grow.
- Establish a long term research program in the area of brain and cognitive science to determine

  -the most effective ways to present data to air crews,

  -the way people process data and reach conclusions, and

  -the best way to alert air crews to rapidly changing external situations.
- Apply the results of these studies to determine what people do best, and how to allow them to do their best. In essence, this task develops a branch of engineering called "cognitive engineering" that stands in relation to brain and cognitive science as structural analysis stands in relation to the theory of elasticity in classical mechanics.
- Use the results from cognitive engineering as a foundation for deciding which tasks to automate to support an air crew in all parts of a mission, including emergency.

In this way the air crews and mission planners in the future will be able to execute their mission in the most effective way.

In following this program, which is a quantitative generalization of the present discipline of human factors, the nation will benefit because the processes needed to develop an understanding of what people do best can be applied to non-Air Force situations. Thus, commercial activities will also benefit. It seems likely that there will be a broad general application for cognitive engineering. The Air Force will profit from establishment of this field of technical endeavor.

Supplemental Information

The ability to effectively integrate man and his/her capabilities into future "warfare systems" is perhaps the critical technical challenge. There will be information overload, lack of situation awareness, human confusion, mistakes, disorientation, the information and control equivalent of PIO's, unnecessary casualties, and missed targets — all to some degree — if integration of crews is not done well.

There is a need for vigorous, focused R&D in this area. It is a true multidiscipline area and involves (at least) control theory, systems engineering, cognitive engineering, information processing, controls and displays, human factors, simulation, and communications and networking. It requires understanding, modeling, and simulating the dynamic interaction among the many "inhabited and uninhabited" elements of the relevant warfare system.

Models and simulations must have necessary fidelity and levels of detail (zeroth, first, second, etc., orders of complexity) depending on the development phase being addressed. This technical area needs to be addressed as an emerging high payoff area. It can be thought of as an evolution of the flight mechanics flying qualities and handling qualities discipline. This discipline has generated a well accepted set of design criteria and guidelines in use worldwide for development and design of piloted aircraft. The criteria and guidelines continue to evolve; however, the focus to date has been on aircraft attitude and maneuver control.

This new area relates to mission control, but goes beyond single vehicle design with fixed external interfaces. Some of our potential adversaries have been very successful in some areas (e.g., integration of HMD, offboresight missiles, high AOA missile launch, and high AOA agile fighters). Some have also suboptimized the benefits of crews by constraining their functions. This was done to simplify the problem so that existing tools could solve it. For example, in integrating fire and flight control, a fully automated system was found to be suboptimal. A certain blending of automated and manual functions worked best.

CAUTION: Unless man is integrated well (at the right place, with the right information, and given the right roles in every mode) our future warfare systems will not be as robust, lethal, survivable, and affordable as possible.

Our long-term development objectives should be to derive the ability to

- accurately model human intelligence capabilities in a rapidly changing environment and to use the models to achieve optimum designs of systems with man in-the-loop,
- thoroughly model human psychological capabilities and achieve optimal designs as above,
- improve human performance via chemical, electro-mechanical, or other means for combat periods,
- design "artificial human intelligent" systems capable of "better than human performance." (e.g., AI systems that act like more than one person-in breadth of intelligence and/or which act much faster (time to decide)),
- counter or exploit enemy's intelligent systems through active countermeasures which are aimed at confusing and rendering ineffective and prone to poor judgment, including manipulation of emotion (psycho/physio warfare) to overwhelm logical functions,
- more effectively train the human and/or human-like elements of a system, and
- use extended forms of genetic engineering to "clone" or otherwise grow organic systems to perform some desired human intelligent functions.

3.4.4 Summary

Feedback control will enable better performance of systems and subsystems at lower cost. Active control of air vehicle subsystems, avionics, engines, inlets, nozzles, adaptive structures, and the aerodynamic flowfield will be achieved with advanced control system architecture design methods.

- Focused development of control system architectures and multi-variable control system design methods is needed.

The criteria used in control system design should evolve from current handling qualities criteria and take into account the human system interface and human cognition and workload.

- Extension of the handling qualities criteria to encompass criteria for all controlled functions and to account for human performance and human system interfaces is needed.

Human performance as a controller is perhaps **the critical technical issue** in the conduct of all future Air Force operations. The technology of "cognitive engineering" will address that through a multidisciplinary approach that requires a major shift to current practice.

- Strong focus is needed developing "cognitive engineering" which is critical for all future system concepts.

3.5 Aircraft Subsystems

3.5.1 Introduction

There are many types of aircraft subsystems, including auxiliary power units, environmental control units, thermal management systems, flight actuation systems, transparencies, landing gears, accessories (e.g., pumps, heat exchangers, batteries, air conditioning), hydraulics, pneumatics, gearboxes, and electrical power generation and distribution. Aircraft subsystems amount to about 10% of a typical fighter aircraft's empty weight and acquisition cost. More importantly, they cause more than 40% of aircraft equipment failures and downtime for repair and add considerably to the logistics footprint required for their maintenance and repair.

This study has identified a number of specific technology areas that can either improve the impact of subsystems on existing and evolutionary aircraft or meet the increased demands of advanced and revolutionary aircraft. In the former case, these improvements can have a very favorable influence on the cost and function of existing and evolutionary aircraft. In the latter case, these improvements will be required to make the advanced and revolutionary aircraft possible.

3.5.2 The More Electric Aircraft

The traditional federated (i.e., functionally independent) subsystems approach often results in under-utilized equipment. In some cases, components are used for less than 60 seconds per flight, and some are essentially dead weight since they are only used if the primary subsystem equipment fails. This under-utilized equipment takes up space and adds weight and cost to the aircraft.

In contrast, the integration of these aircraft subsystems can result in revolutionary reductions in weight and life cycle costs while increasing the flexibility and survivability of the vehicle. Furthermore, the technologies that enable subsystems integration are dual-use and have a broad range of commercial applicability. The comprehensive USAF program aimed at bringing these changes about is known as the More Electric Aircraft Program because its main thrust is to make maximum use of electricity for power and control functions.

The More Electric Aircraft Program has three identifiable stages, the first of which is already underway. During the present stage, a number of retrofitable subsystem concepts for a wide range of aging aircraft are being developed and demonstrated. They include maintenance free batteries/higher power density batteries, heat pipe and electrostatic heat exchangers, higher power density electronics/motors, and electric brakes (to eliminate hydraulic fluid fires).

By the year 2000, an integrated subsystems suite is to be demonstrated that will include such concepts as a thermal energy management module, electric flight actuation, fault tolerant electrical power distribution, an integral starter generator (external to the engine), and exhaust nozzle cooling. These were selected based upon studies that showed that this work would, relative to F-22 subsystems requirements, reduce procurement costs 3-5%, reduce life cycle costs 3-4%, decrease takeoff gross weight up to 5.5%, and decrease aircraft volume up to 9.1% or increase range up to 20%.

By the year 2010, an integrated subsystems suite is to be demonstrated that will include such concepts as high temperature/low cost power electronics, advanced heat exchanger/thermal management concepts, affordable exhaust nozzle/nozzle cooling, integral starter generator on the engine shaft, magnetic bearings, high power density power electronics, and high power density integrated power system. These were selected based upon studies that showed that this work would, relative to F-22 subsystems requirements, reduce procurement costs 8-9%, reduce life cycle costs 5-6%, reduce takeoff gross weight up to 8%, and decrease aircraft volume up to 12.7% or increase range up to 28%.

The same technology advances can provide a 2.5-fold increase in electric power system reliability, eliminate hydraulic systems for transports by 2000, eliminate engine gearboxes, and provide a 4- to 10-fold increase in electric power system reliability by 2005. The logistics footprint required to support future aircraft will also be dramatically reduced or eliminated.

Finally, the engine shaft integrated starter generator can conveniently provide the 1-2 megawatts of power to produce high energy laser or microwave beams for either defensive or offensive purposes. Since the rotating shafts are normally transferring tens of megawatts from the turbines to the compressors, briefly withdrawing one megawatt or so will have a relatively small impact on engine operation. An example of a related special purpose power missile program using a cryogenic aluminum generator and a small jet engine to produce 4 MW of continuous power is shown in Figure 3.5.1.

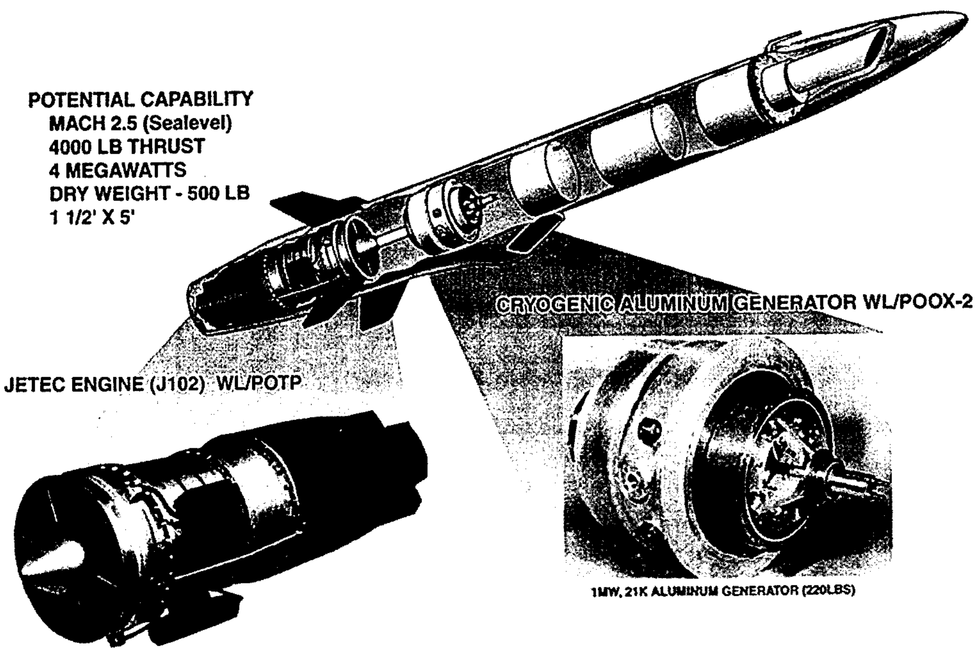


Figure 3.5.1 Special Purpose Power Technology

3.5.3 Endothermic Fuels

Fuel is the primary coolant for aircraft and engine subsystems. Current vehicles meet their energy dissipation requirements by heating their fuel to temperatures above its thermal stability limit. This causes the fuel to degrade and plug the fuel manifolds, main burner fuel nozzles, and afterburner spraybars, causing the engine performance to decrease and the maintenance burden to increase.

The cooling requirements for aircraft are increasing rapidly with time for several reasons. First, dependence on electrically powered avionics equipment is increasing and with it the amount of ohmic heat to be removed. Second, temperatures throughout the engine are increasing so that additional cooling is needed to protect the engine structures and the surrounding airframe. Third, flight speeds are increasing and, with them, the aerodynamic heating, especially for hypersonic vehicles. Fourth, laser and microwave beam weapons will generate, while operating, large amounts of waste heat.

Consequently, the cooling or heat sink capacity of fuels must be increased in order to make other aircraft advances possible. A program is already in place to increase the thermal stability of JP-8 from 325 °F to 425 °F by means of an additive package that will raise the cost by about $0.001 per gallon and be available by 1998. This fuel, known as JP-8+100, has been flight tested in current fighter engines with remarkable reductions in coking and plugging. This fuel is essential for the next generation of fighters. Plans have been made to push the thermal

stability limits of hydrocarbon fuels to their limits, perhaps as high as 900 °F. The resulting fuel, known as JP-900, would be available by 2003 and could be very beneficial for the next generation fighter.

Ultimately, considerably higher fuel cooling capacities will be needed to directly cool the surfaces of vehicles flying at Mach numbers above about 5 and to minimize the dependence on exotic materials of engines based on IHPTET Phase II and Phase III technologies. The fuel sink capacity of ordinary hydrocarbon fuels can be increased 10-15 fold by using catalysts to cause their controlled chemical decomposition to ethylene and other light ends. These reactions require energy addition in order to break the chemical bonds and are therefore referred to as endothermic reactions. The fuels involved are correspondingly known as endothermic fuels.

The chemical energy absorbed by the endothermic fuels in not lost to the vehicle, but is recovered during the combustion process in the engine. Moreover, the ethylene and other products of the chemical decomposition have lower molecular weights than the original fuel and therefore mix and burn more easily, leading to shorter combustors and/or higher combustion efficiencies.

Depending on the specific application, endothermic fuels will enable flight Mach numbers in the range of 6-8. They could be available as early as 2005, provided that adequate investments are made.

3.5.4 Turbine Engine Lubrication Technology

Lubrication systems are a vital part of every engine. The demands on them are growing as engine temperatures and rotational speeds increase. At the same time, there is a desire to simplify them or increase their reliability.

Ten years from now the majority of gas turbine engines will still employ liquid lubricants. The lubricants will have to operate at higher temperatures, while cold basing will continue to require that they function at low temperatures. These extreme temperature constraints will force the fielding of perfluorinated (PF) lubricants, provided that basestock and additive technologies have evolved to make them practical. Bearing materials and coatings must also be developed to deal with the corrosivity of the PF lubricant as it is thermally stressed.

Lubeless, magnetically levitated bearings may be crucial to meeting the IHPTET Phase III temperature and rotational speed requirements for the mechanical system, but high temperature magnetic materials are not well developed, back-up systems for damaged or failed primary systems do not exist, and there is no industrial base for producing and supplying high temperature magnetic materials and components.

Alternative lubrication schemes, such as vapor phase deposition and solid coatings, show promise for expendable engines, but the underlying surface phenomena associated with the performance of these materials is not established. The applicability of these materials to expendable engines must be demonstrated and extended, if possible, to ground vehicles or pilot-rated engines.

Engine diagnostics through in-line oil analysis will need to adjust to single fluid engines that have no recirculating lubricant. In these systems, engine health must be monitored through

evaluation of the vapor phase leaving the bearing compartments before entering the combustion chamber.

Simultaneously, hazardous materials must be eliminated from lubricants, as well as process and test methods. We need a biodegradable, non-toxic family of lubricants.

These important turbine engine lubrication system goals can be reached by the year 2005, provided that adequate investments are made.

3.5.5 Thermal Energy Management System

Avionics cooling capacity is currently 15 to 50 watts per square centimeter (W/cm2) with flow-through rack cooling design. Future avionics may require 100 to 200 W/cm2 cooling capacity. Flow-through systems are in development to meet this near-term need, but the technology is moving toward micro-channel cooling concepts capable of cooling capacity of thousands of watts per square centimeter. These devices will require laboratory verification and flight demonstration.

Thermal management components such as heat exchangers currently exhibit low reliability, especially at higher engine air bleed temperatures of 1100 °F. Compressors and bearings are the top failure item in the aircraft environmental control system (ECS). Carbon-carbon heat exchangers are in development which offer 50% weight and volume reductions while increasing reliability under temperatures up to 1300 °F. Magnetic bearings are being investigated to replace the compressor air bearings. Both the carbon-carbon heat exchanger and the magnetic bearings need technology demonstrations.

Design of the overall vehicle thermal management system is not approached from a total systems viewpoint. Trade-off studies are performed at the component or module level due to our inability to model the entire system. The thermal management system is usually designed for the worst point in the flight envelope rather than the most cost-effective design for the entire mission profile. In the future, we will develop and use integrated system-level modeling and simulation. We envision a "virtual bird" design/assessment capability for optimizing the total thermal energy management at the aircraft (weapon system) level. This will allow rapid performance and trade-off studies to develop optimal designs. Hardware-in-the-loop testing will verify the chosen design.

3.5.6 Ground Operations (Takeoff and Landing Systems)

Aircraft tires on high performance aircraft (e.g., F-16, Block 30/40/50) are currently limited to less than 12 landings per main gear tire. The AF is developing an extended life tire with the goal of 50 landings per tire, which is the F-22 requirement. We need better tire design and analysis methods and extension of the speed capability of tires to support hypersonic vehicles, which may have takeoff/landing speeds up to 400 mph.

Multi-regional wars and special operations aircraft may require combat aircraft to operate from ill-prepared landing fields. This type of operation could require broad tires to takeoff and land on softer surfaces at the price of some drag increase. Clearly, this is an application of the modular concept.

For the landing gear mechanism, corrosion and weight are issues, resulting in high maintenance cost and performance losses. The landing gear fraction of airframe structural weight is increasing to over 5% as the airframe structure gets lighter due to composites, etc. Composites have not been successfully applied to landing gears. The AF is now investigating titanium metal matrix composite (TMC) landing gear components. TMC is expected to greatly alleviate or eliminate the corrosion issue. Health-monitoring and diagnostic schemes need to be applied to landing gear systems. Such a program is being planned. Landing gear shimmy (usually nose gear) is a problem on nearly all developmental aircraft, resulting in costly delays and fixes. A much better analysis of this dynamic structural problem is needed.

Eletromechanically actuated brake systems are in development which reduce brake wear and increase brake/wheel/tire performance. These will lead to longer life brakes with higher heat capacity compared to current systems. Further, electric brakes add a margin of safety to emergency situations such as rejected take-off (RTO).

Another important subsystem, especially for cargo aircraft, is material handling equipment (MHE). The AF has to deliver MHE to the combat zone if it is to be in close proximity to the ground force units. Current cargo handling operations are very labor intensive. An automated robotic cargo handling system needs to be designed and developed. The AF needs to look at commercial cargo handling systems to see what could be adapted to meet AF needs. Some cargo handling concepts are integral to the aircraft while others are ground-based. The goal should be to increase productivity while decreasing labor requirements.

3.5.7 Transparencies

Transparencies for AF aircraft are high maintenance items. Fabrication is currently labor-intensive. Current transparencies do not meet the projected future requirements for laser/microwave protection and low observability characteristics while still meeting birdstrike protection and crew escape requirements. Mach 2.5 is about the aero-thermal limit for current light weight plastics used in transparencies.

Our vision for the future is to develop a transparency system through integrated design that will reduce AF cost of ownership by 50%. Key technologies are injection molding, bird dispersal techniques, recyclable materials, variable tinting through smart materials, and light weight transparencies for high speed flight.

3.5.8 Aircrew Escape

Current ejection seats have inadequate protection for the crew member during high speed ejections. The ACES-II seat has a 66% rate of major injuries or fatalities for ejection in the 500-600 KEAS range. The seat envelope for safe ejection is smaller than the aircraft flight envelope. For example, if an emergency occurs at Mach 2, the crew member has to wait for the aircraft to slow down before a safe crew egress is possible. This is clearly unacceptable. Another issue is that current seats do not safely eject the smaller pilot, more of which are expected as females are incorporated into fighter and bomber crews .

The future vision is to have an advanced light weight, reliable ejection seat or system which is compatible with the full flight envelope for fighter/attack aircraft. For hypersonic global reach aircraft (Mach 8 to 12 or even higher), an escape capsule or system is probably the

only solution. Waiting for even one or two seconds after an egress decision is made is unacceptable. We need crew egress on-demand. Key technologies are eject propulsive control, seat/capsule stability under any escape condition, and controlled descent and landing.

3.5.9 Precision Airdrop (Material and Personnel)

For true global reach, the AF needs the option of a precision (a few meter accuracy) airdrop from altitude and speed conditions where the delivery aircraft is survivable. Currently, high accuracy is only possible from low altitudes, which is hazardous to the launch aircraft and crew.

High altitude drop accuracy is limited by knowledge of winds, lack of a precision guidance/navigation package, and inaccurate calculation of the computed air release point.

The future vision is for precise airdrop from high altitude (35,000 ft) to a designated point on the ground with 10 m circular error probable (CEP), for a wide variety of payloads. Key technologies are GPS sonde and LIDAR (light detection and ranging) to provide real-time wind data over the drop-zone, guided navigation through GPS/INS and electro-optic or laser designation, and a time-variant computed air release point so that a parafoil can hit the designated point from a wide variety of launch points (off-set, fly-back, etc.)

3.5.10 Aircraft Fire Suppression

Current aircraft fire suppression systems use Halon 1301, which is no longer in production due to environmental protocol. The AF (DOD) is searching for a Halon 1301 replacement which will work in all required areas of the aircraft, including dry bays and engine nacelles, where fire suppression is needed. Key technologies being investigated are solid propellant gas generator fire suppression systems, inflatable air-bag fire suppression, and machine-vision fire detection system.

3.5.11 Combat Damage Assessment and Repair

Subsystems for combat damage assessment and on-board or off-board systems for combat damage repair can increase sortie generation in the combat environment. Computer-aided assessments of battle damage can be used to define the minimum-time repair concept with the materials available in the field. This can be a powerful force multiplier to generate additional sorties. On the other side of the combat damage equation is the reduction/avoidance of combat damage through vulnerability reduction. Vulnerability reduction consists of four major efforts: vulnerability assessment, threat model and simulation, threat penetration model, and live fire testing to validate the combat damage.

3.5.12 Summary

Aircraft subsystems permeate every vehicle. They are frequently either the villains or unsung heroes of reliability, survivability, maintainability, and affordability. Much can be done to dramatically improve their individual and collective performance for existing and future air vehicles. In the longer term, as cooling and requirements grow substantially, the technology of the thermal management subsystems will become enabling in the sense that it will place the upper bound on allowable heat dissipation. Power conditioning and energy storage techniques,

particularly for high power laser and RF weapons, are the building blocks for many airborne systems, from future attack aircraft to HALE, and must therefore be continuously improved.

We therefore suggest the following:

- The More Electric Aircraft program should be vigorously pursued.
- Advanced thermal energy management systems with cooling capacity of 200 W/cm^2 should be vigorously pursued.
- The JP-900 and endothermic high heat sink fuels programs should be vigorously pursued.
- Since current ejection seats provide inadequate crew protection during high speed ejections, development of a new ejection seat with advanced aerodynamics, control, and propulsion for safe ejection at 600 knots should be pursued.
- Precision airdrop from high altitudes should be deveolped to increase delivery aircraft survivability. We recommend technology demonstration of precision airdrop technologies such as GPS/INS guided navigation, guided parafoils, and GPS-sonde or LIDAR to provide wind corrections in the drop zone.
- Improved aircraft fire suppression systems using non-ozone-depleting chemicals are urgently needed.

Our vision for the future of combat damage assessment and major repair is built-in subsystems to assess damage, self-repairing/self-healing structure, and a computer-aided repair technique which would indicate to the repair team exactly what is needed to be repaired to restore the aircraft weapon system to the desired operational capability.

3.6 Design Integration

3.6.1 Introduction

Technology has been described as "any systematized practical knowledge based upon experimentation and/or scientific theory, which enhances the capacity of society to produce goods and services, and which is embodied in productive skills, organization or machinery."[8] Integration of the diverse technologies involved in building an airplane assumes special importance because there is a need to account for the potential for strong interactions between system components and their supporting technologies. This interaction may be favorable or unfavorable to the component technologies or the system. For integration to take place, the system component interactions must be understood, quantified, controlled, and exploited. As a result, system integration is itself a technology within the broad definition given.

All of the aircraft design concepts presented in this report require that special attention be paid to technology integration such as electronics integration, aero/propulsion integration, and aerodynamic/structural (aeroelastic) integration. Two factors make this task difficult. First, the

8. B. Gendron, *Technology and the Human Condition*, St. Martin's Press, New York

number of new civil and military aircraft designs has declined dramatically over the last decade so that the wealth of experience from the past and, perhaps, the promise for the future are disappearing. Second, a more severe threat demands radically new design concepts for which technologies must be tightly coupled and for which no data base of experience exists.

Advanced aircraft design efforts in the United States have slowed because science and technology funding continues to decline. On the other hand, specialized design computer codes that enable the design team to increase productivity and explore the myriad of "what ifs?" required for effective component integration are under development in many places throughout the world. The routine use of structural finite element codes and aerodynamic paneling codes, as well as CFD codes, has sharpened the detail available to design teams very early in the design process.

Computer graphics codes, structural finite element analysis codes and planning and scheduling software codes are ways that design teams use information systems to improve product quality and to reduce time required to introduce new aircraft. For instance, computer graphics were used extensively in the design of the Boeing 777, avoiding an expensive physical mock-up. With continued development, such types of software could be effective and inexpensive ways for industry to improve quality and even tie together and improve university design teaching and research efforts.

This section discusses improvements in design integration technology required to support the development of complex systems at a time when Air Force budgets are being reduced. Integration technology is information based and has become more viable because of advanced analytical tool development such as structural finite element methods, computational fluid dynamics (CFD), and advanced data base management. Analytical tools — coupled with high speed computer networks and appropriate data management protocols — give a design team the capability to work nearly concurrently with each other and to exchange critical design information so that one effort does not operate independently of the other.

The following sections describe the issues and potential of aircraft design integration technology and formal optimization methods. This discussion focuses on the way these tools might be used by design teams to

- change the design process,
- decrease cost, and
- accelerate use of new technology to improve future military aircraft.

Computer aided design tools can never replace the design team. However, their use by design teams is becoming more widespread and accepted, making high quality aircraft design more affordable. The support and development of these advanced design tools and their rational integration into the design process is important to the future of the Air Force. Of particular importance to the improvement of the design process is research into and development of cost models that can be used by design teams early in the design process. The integration of cost concerns early into the design process, together with performance objectives and constraints, is central to affordability objectives.

3.6.2 Cost and Interdisciplinary Optimization

Design blends together qualitative, judgmental, and creative attributes of human thinking with quantitative, precise algorithmic operations of computers. Computer applications liberate design team members from tedium and quantify trade-offs between technologies. In addition, computer applications will allow the airplane design team to

- identify relationships between mission performance metrics and system cost,
- develop alternative designs and eliminate unsuitable concepts,
- define cost/benefits of adding new technology, and
- increase chances of "first time" production success.

Computer applications can also change the design process structure from today's sequential process to one that is nearly simultaneous or "concurrent." The strategy of concurrent design is to have system component design decisions coordinated or integrated so that detailed design efforts in one area do not proceed too far or too quickly without feedback from other areas. As a result, efforts are not wasted defining details that will later become obsolete.

Figure 3.6.1 The Typical Aircraft Design Process

Concurrent design relies heavily on computer analysis, high speed computer networks, and appropriate data management protocols to produce high-quality design solutions in less time than a sequential process. The impact of the use of computer applications to integrated design is summarized in Figures 3.6.1 and 3.6.2.

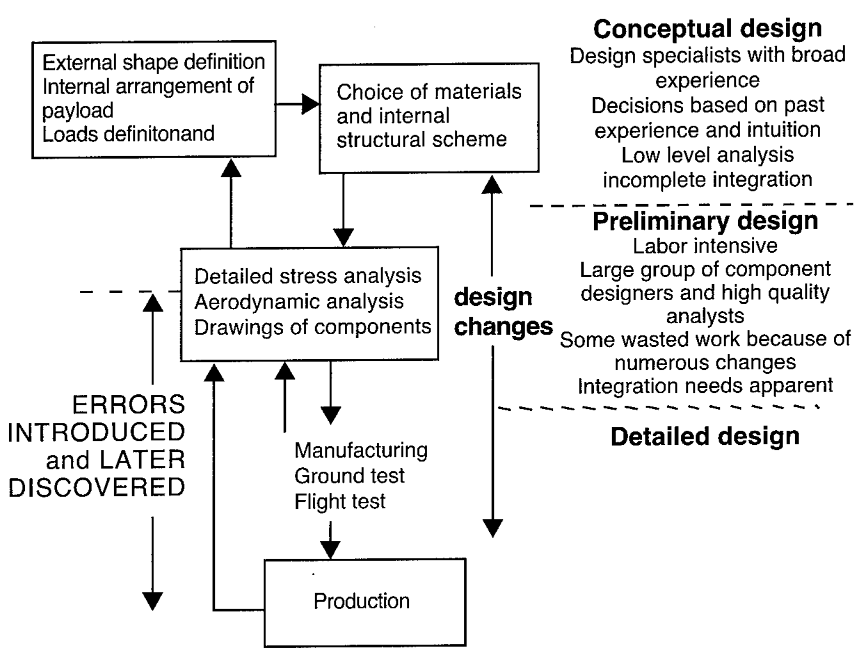


Figure 3.6.1 The Typical Aircraft Design Process

Figure 3.6.1 shows the organization and flow of most design processes today. The first stage - conceptual design - is usually the most creative and innovative stage. Here, the designers must collect and assimilate as many relevant facts as possible. The success of the design effort depends heavily upon the training and previous real-world experience of the design team. The output of this effort is a set of possible configurations which must be evaluated for their merits. The relatively low level of configuration detail available at this stage often precludes identification of system integration problems or opportunities.

The availability of experienced personnel for the evaluation phase is also critically important to the design effort. Details that might escape the eye of a novice may be readily apparent to an experienced person without any calculations. Time is extremely important here, also, so that analysis is limited by time and money. In particular, only modest amounts of structural analysis are done at this stage, despite the strong correlation between structural arrangement, weight, and cost. Even with extensive computer capability, there is a long period of time during which design changes are required and errors in judgment (caused by lack of information) are introduced, discovered, and repaired.

Preliminary design begins to blend with conceptual design as configuration alternatives are eliminated. To add greater detail and fidelity to the conceptual design and begin preliminary design, system components must be designed or acquired. For some components there may be many design choices. Given time constraints and limited information, the component designer/selector makes decisions based upon his/her experience. Sometimes, mathematical optimization methods are used.

Optimization methods, discussed later in this section, may be of only limited value for some portions of the design process. For optimization processes to be of value to the design process, it is important to understand and state the design constraints clearly and completely. This understanding and completeness may not be possible in some complicated design processes. The relationship of cost to some design decisions is one design process with incomplete understanding.

Manufacturing concerns also begin to appear during the preliminary design process (the lines shown in Figure 3.6.1 as definite boundaries between the design phases are really rather fuzzy). The success of the design now depends on the ability to define in great detail every part and every process needed for production. Design team success depends on the ability to produce the product at a cost estimated long before this detail was available. Experienced designers will have considered production early in the process, but not in the detail they might prefer. Like internal structural definition, manufacturing and cost concerns lie far downstream from the creative conceptual process outlined in Figure 3.6.1.

The Air Force is shifting from technologies that almost exclusively emphasize aircraft and system performance to a more balanced approach that considers cost or affordability with performance. At the present time, we do not have the capability to do meaningful trades, with the fidelity required, between elements of cost and elements of system performance. One of the key enabling technologies that needs much more emphasis is reliable, accurate cost prediction.

Cost modeling needs to be recognized as an important part of the preliminary design process. The strong relationships between decisions about mission objectives and cost of the vehicle need to be scientifically examined so cost estimation is recognized as a science. Air Force

planning must also accurately define the value of new technology to its systems. This assessment must accurately quantify the impact of new technology development, assess the risks, and identify "holes" in the technology ensemble necessary for mission success.

The impact of computer use in the design process lies not just in concurrent design, but also in its potential to enrich the design process. Computer applications speed up the analytical processes supporting design and add accurate information to the design process. The design process can benefit even more from computer analysis if it is organized and augmented as shown in Figure 3.6.2. In this figure, a new analytical step is introduced to conceptual design. An analysis of the idealized configuration structure is added to determine the optimal load carrying structure, including internal details such as advanced composite material laminate arrangements or even the structural "skeleton" of the airplane. Many details are missing from this analysis, but the essential character of the internal structural arrangement is captured here and transmitted to the design team.

With the essential information of internal structure available to the design team, structural design and manufacturing can enter the conceptual design process earlier. Adding analytical information to the conceptual design phase slows the design process, but it provides information such as simple advanced composite laminate design information. It also provides an indication of the effects of materials choices on aircraft weight and manufacturing cost.

In the process described by Figure 3.6.2, manufacturing advisors are added to the conceptual design team to alert the design evaluators to the manufacturing consequences of their decisions. It also allows experienced designers to work closely with analysts at this early, critical stage of design. There is immediate feedback to the configuration geometry team, and a preliminary message is sent to the manufacturing and the cost management teams.

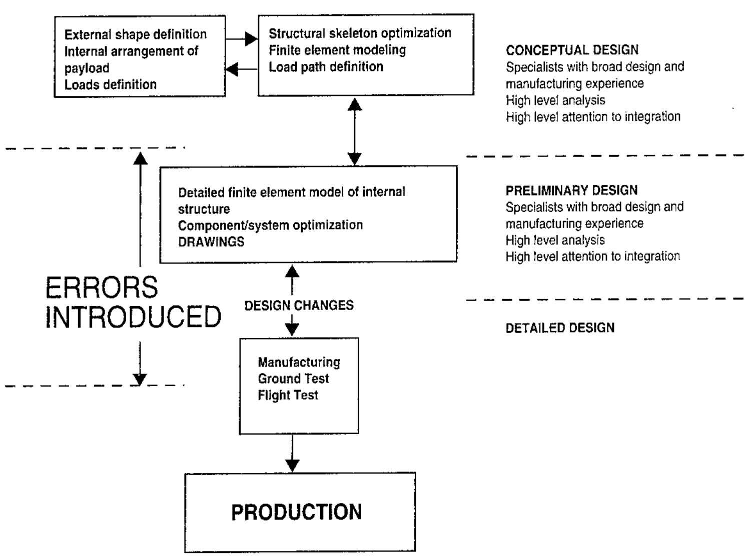


Figure 3.6.2 Design Process with High Speed Computing to Ensure Multidisciplinary Optimization, Manufacturing, and Cost Issues are Identified Early

There are other advantages to augmenting the design process with computer applications. With more design information available, additional elements of interdisciplinary optimization are included during conceptual design. In addition, the time required for each design iteration can be reduced. Moreover, the use of a common geometric data base and tight configuration control reduces mistakes. Finally, experienced designers are brought together with competent analysts and manufacturing people so that experience at all levels is exploited.

Integration of technologies and design functions occurs at several different levels. Many different types of computer and software tools have been proposed to help the design of air vehicle systems and subsystems, and to determine which technologies have the greatest payoffs for these systems. We have sub-divided the discussion of these tools and developments into several sections. The first of these sections is computerized structural design and its relationship to cost. In addition, we review the potential to address problems related to smart skins.

Computer Aided Structural Design

DOD studies indicate that 70% of life cycle costs are determined during conceptual design. On the other hand, design cost is difficult to predict early unless we have experience with the particular processes used for manufacture. The overriding requirement of defense "affordability" is that we have access to reliable cost prediction and the ability to quantify trades between cost and expected mission performance. Structural design choices have an impact on system cost, both in time required to manufacture the structure and later maintenance costs. Early cost estimates, when fed back to other design team members, can alter design decisions and must be used as early as possible in the design process.

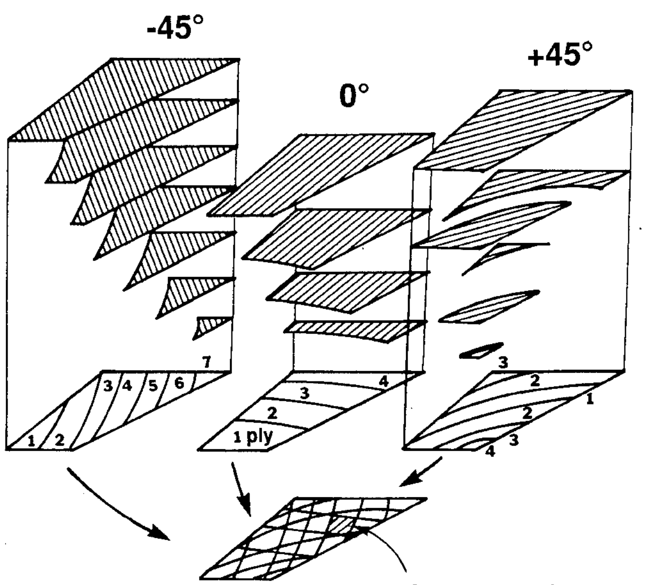


Figure 3.6.3 Advanced Composite Material Wing Laminate Optimization

The need for materials selection and optimization is exemplified most by the emergence of advanced composites as a construction material. The use of advanced composite materials gives the designer many more degrees of freedom, but there is a bewildering array of acceptable ply orientations or stacking sequences for a single mission when only strength is considered. Figure 3.6.3 illustrates the complexity of advanced composite material laminate design for a wing structure. Because the structure has many different loading conditions, computerized optimization is necessary to sort out the best design candidates.

The past two decades have produced specialized optimization codes for structural design. These codes are capable of defining an arrangement of advanced composite plies to sustain load sets for an aircraft mission. During the past few decades, the Wright Laboratory Flight Dynamics Directorate has sponsored development of computer codes such as the TSO code and FASTOP. TSO and FASTOP were used for design evaluations of aircraft such as the X-29 research aircraft, whose tailored composite wings were designed to resist divergence and flexibility, but induced flight mechanic instability. This is one type of aircraft that cannot be built efficiently without advanced composite optimization or "tailoring." The X-31 also uses tailored composites in its vertical tail to reduce weight and improve high speed yaw maneuver performance.

The USAF Wright Laboratory Flight Dynamics Directorate has also led efforts to develop a common integrated computer code called ASTROS for multi-disciplinary optimization that includes interactions among structures, aerodynamics, and automatic controls technologies. This code is an ensemble of codes linked together to provide detailed information such as sensitivities to design changes as well as optimal configurations. Major efforts at NASA Langley Research Center are also being devoted to development of multi-disciplinary design methodology for transport aircraft. Advances in CFD technology required to support the loads definition portion of this process are discussed in detail in Section 3.1.4.

Other major efforts in automated design are occurring in Europe, including work in the former Soviet Union. The Russian RIPAK computer code is a development that provides designers with structural design information. RIPAK adds a step to define structural load paths to the conceptual design process organization shown in Figure 3.6.2. This information is then presented, together with the geometric shape of the airplane, to experienced practical designers to help them perform their task.

Structural Cost Estimation and Modeling

The increasing complexity of air vehicles and the myriad of conflicting mission requirements demand reductions in risk. The amount of information available early in the design, contained in structural/aerodynamic/control optimization codes, has not been exploited by cost estimation teams. Small companies with markets for specialized parts are beginning to use computer models to link portions of the design process, beginning with materials choices and extending to part size, shape number of parts and, finally, cost.

Cost information must be considered by a design team as early as possible. The ability of small suppliers to accurately design component parts using computerized design/estimation procedures can speed the introduction of appropriate science and new technological processes into product design to maintain cost competitiveness. This ability appears to be possible to a greater extent than now available. Accurate computer models can produce a high quality part

quickly and at lower cost. If accurate cost models can be created to link design and manufacturing in complex processes, particularly to those processes which use advanced technology for which there is no empirical data base, we are more likely to produce more affordable designs.

Subsystems Level Integration (SLI) Methodology

At the sub-system level, one particularly important integration area is electronic packaging and the integration of these packages into the airframe. Future aircraft requirements are forcing volumetric and weight reductions for all aircraft components. As a result, many separate components are in very close quarters where physical interactions are strong. These components must be designed as one interwoven, integrated system.

Subsystems Level Integration Methodology is a developing technology to integrate complex systems that are functionally diverse and physically separate into one multi-disciplinary technological entity. For example, SLI is essential for small unmanned vehicles, the FotoFighter concept (with electro-optical and RF sensors radiating powerful amounts of radiation), VSTOL, STOVL, VTOL, and affordable lightweight aircraft.

At the present time, many individual component technologies are physically separated, shielded, and individually optimized. If interference is discovered during the design process, component designs are changed individually until the interference becomes tolerable. This slows the design process, as was indicated in Figure 3.6.1. No "cross-talk" between disciplines is encouraged or permitted. Individual technology disciplines involved in SLI include

- composite structures,
- low signature mechanisms,
- mission sensors, avionics,
- thermal conditioning,
- electrical power, and
- condition monitoring systems.

An example of this type of integration is the design of an a multi-functional, advanced aircraft skin structure. The multi-layer character of composite structures has the potential to allow some items to be interwoven or enclosed within structural components. Micro-processors, antennae, and sensors (electro-optical, acoustic, chemical, biological, radiological, strain, and force) are small enough to appear as layers in the structure. Fiber optics, heat pipes, and patterns of copper, silver, or gold networks provide signals, thermal conditioning, and electrical power. Micro-electromechanical Machines (MEM's) and nanostructures provide the promise of miniature embedded machines supplying mechanical power, force, and motion for sensors and switches.

Development of smart skin arrays is an example of an area where SLI is essential. Smart skins may contain miniature EW, radar, and communication antennae enclosed with signal processors and integrated with fiber optical signal, copper power, and heat pipe cooling networks embedded in a composite structure. The composite structure can be a primary aerodynamic surface or control mechanism such as a leading edge flap. The flap may also have RF, EO,

visual, and acoustic signature reduction capabilities. All of these items can interfere with one another. Their design must be addressed as a systems-level integration technology problem.

Additional applications using SLI technology include:

- Smart aircraft and propulsion structures incorporating machinery that monitors and diagnoses the health of the apparatus using miniature sensors, processors, and networks.
- Helmet systems that integrate helmet mounted displays, head and eye tracking, laser eye protection, acceleration, impact, pressure, temperature, chemical, biological, and radiological protection with consciousness, workload, and fatigue monitoring.
- Advanced integrated cockpits to encapsulate the pilot and provide protection for the pilot's whole body, provide interface between the pilot or crew person and the aircraft, and provide emergency escape.
- Integrated flight, propulsion, and nozzle control systems with MEMs.

3.6.3 Affordability/Manufacturability

Introduction

As mentioned previously, the Air Force is shifting from technologies that almost entirely emphasize performance to a more balanced approach which thoroughly considers cost along with performance. This is being brought about by Integrated Product Process Development (IPPD) teams involving all the relevant disciplines and all phases of system life, from design to manufacturing to operation and logistics to retirement/disposal. One of the key enabling technologies that needs much more emphasis, if the Air Force is to balance affordability and capability, is reliable, accurate cost modeling. Cost modeling needs to be viewed as a science, not as a "black art."

Manufacturability

Manufacturing is one of the keystones of affordability. The design of the system can have a significant influence on the cost and flexibility of manufacturing. In addition, manufacturing process improvements have great potential to reduce cost.

The current Lean Aircraft Initiative (LAI) builds on the Massachusetts Institute on Technology (MIT) assessment of the worldwide automotive industry, but focused on the aircraft sector. It is a unique pilot program of government and industry collaboration across an entire industrial base sector to reduce costs and improve quality in the aircraft industry.

There are four focus areas in LAI: product development, factory operations, supplier systems and relationships, and organization and human resources. The LAI is structured to determine which focus areas apply to the aircraft industry. Lean manufacturing payoffs in the auto industry include 1/2 the human effort in the factory, 1/10 of in-process inventories, 1/2 the factory space, 1/8 the number of suppliers, 1/2 the engineering effort, 1/2 to 1/3 the develop

ment time, 1/3 the defects, 1/4 the scale of production and 4 times the range of products. Similar large payoffs should be available in the aircraft industry with manufacturing research and development over the next 20 years.

Virtual Manufacturing

One of the key areas in manufacturing research to reduce cost and improve producibility is known as "virtual manufacturing," which is intended to provide insight to the manufacturability, affordability, and supportability of new weapons systems prior to the commitment of large production and operations resources. In addition, virtual manufacturing can allow design teams to maintain manufacturing proficiency without actually building products. Virtual manufacturing, an integrated, synthetic manufacturing environment, meets these objectives by providing the capability to design and simulate manufacturing "in the computer."

Key technologies to support virtual manufacturing are robust modeling and simulation of the manufacturing process based on verified and validated models whenever possible; information technology to develop, manage, and distribute information; and information infrastructure.

Affordability

The term "affordability" appears in many places in this report. Affordability is used in many broader discussions of weapon system development, procurement, and operations. Affordability involves trade-offs against a number of external factors as well as direct cost, cost of development, cost of procurement, and operational and maintenance costs. Many of the factors associated with affordability are quite beyond the knowledge and control of the aircraft system designer.

Cost Modeling

Historically, costs associated with development, procurement, operations, and maintenance are determined after the fact on the basis of a regression analysis. The independent variables include several measures of system performance, the expected number of weapons systems to be purchased, and perhaps the duration of the development and procurement rate. The resulting regression is often termed a "cost model." The estimates provided by this model are often inaccurate. Cost determinations are not fully defined and cost estimation is an immature technical discipline. Because of the important part cost modeling plays on affordability, one of the major recommendations of this study will be to invest more resources in the "science" of cost modeling. In summary, cost modeling is the key to affordability. If we can't accurately predict life-cycle cost and have insight into the contributors to cost, we will have little hope of significantly reducing the total costs of Air Force systems.

Cost modeling covers many elements and many phases in the design process. Unique models exist for each phase of the life cycle (design, production, operating and support), for varying levels of detail (top, intermediate, component), by air vehicle component (airframe, engine, avionics), and for different estimating techniques (parametric, analogous, grass roots). The current government and industry focus is on making these models account for new technologies, materials, manufacturing processes, and maintenance concepts, attempting to move away from the traditional "weight based" models.

The Air Force's Modular Life Cycle Cost Model was developed in the early 1980's and became the accepted advanced technology conceptual level cost tool used by the Air Force and industry. The last update of this model occurred in 1986 and the model has remained unchanged since then.

Technology advances have created a need for more realistic models that estimate life cycle cost (LCC). Parametric models rely upon data from current operational systems and therefore do not adequately predict the costs of advanced technology. For example, the Cost Advantage model is an expert system that provides design guidance, advanced manufacturing analysis, producibility analysis, and predictive cost analysis. The model contains knowledge bases in resin transfer molding, composites, injection molding, casting, machining, sheet metal, and assembly processes.

3.6.4 Modeling and Simulation

Modeling and simulation (M&S) supports two broad Air Force needs: analysis and training. Analysis is needed for system design, operational planning, and definition of future acquisition requirements. Available options are evaluated in terms of quantitative measures of merit. The models best suited for this purpose are constructive models (digital representations), stochastic in nature, requiring many iterations and operating 100 to 10,000 times faster than real time, yielding estimates of probable outcomes over a realistic range of conditions.

Training models and simulations usually run in real time and rely heavily on man-in-the-loop simulation. It is now possible to link remote, virtual, and man-in-the-loop simulations together in real time to support wargaming and operational exercises at the mission and campaign level. As telecommunication and computing technologies advance, Distributed Interactive Simulation (DIS) capability may ultimately permit "mission planning on-the-fly" and high fidelity mission rehearsal before combat missions.

There are generally four levels of M&S analysis models, ranging from general to specific: a general campaign level pitting friendly forces against opposing forces; a mission level pitting a friendly force element against an opposing force element in a specific battle action; engagement level pitting one or more friendly weapon system(s) against one or more opposing weapon system(s) in a combat environment; and, the most specific, an engineering level of M&S which specifies the performance of a system, subsystem, component, procedure, or physical process. Engineering level M&S technologies are an intrinsic part of technology development thrusts.

These features of most "analysis" models make man-in-the-loop contributions generally impractical since the human operator can only operate in real time. In the future, with careful attention to variable resolution M&S design, options may become available to incorporate man-in-loop virtual simulations at critical junctures in an analytic simulation to capture the realism and variance associated with human operator decision making. This added capability will significantly enhance decision-support for the acquisition process.

Major technology investment needs are required in most flight vehicle modeling and simulation technical areas. Increased emphasis is needed in many areas, for example structural modeling, flight vehicle/weapons separation trajectory analysis, propulsion-flight vehicle inter

actions, and enhanced in-flight simulation. At the component level, computer tools are needed to examine physical phenomena such as structural vibration, navigation, guidance, and control.

In many areas such as flight vehicle propulsion modeling, computational fluid dynamics, and structural finite element analysis, there has been extensive work in the air vehicle and propulsion technical community which has produced a number of high quality codes which are anchored to a strong base of experimental data.

With the current emphasis on internetting multiple models for various systems and subsystem components, the S&T community will not only need to develop new technologies, but also assess/modify current modeling capabilities for their applicability to an internetted approach. However, major technology gaps will still exist that require development of software design architectures, common data bases, standard model verification, validation, and analysis (VV&A) tools, common environmental and threat models, and standard computer architectures that can operate using massively parallel processors.

Future air vehicle and propulsion modeling and simulation technologies will emphasize stronger inter-model compatibility through validation and verification of documented existing tools. In addition, newly developed models will emphasize the standardization issues in attempt to improve the transportability of data bases and critical vehicle parameters among various hardware interfaces and software operating systems.

4.0 Infrastructure

Supporting the air vehicle concepts and their enabling technologies is an infrastructure which itself represents significant technology management and financial challenges. Included in this section are ground test facilities, flight testing, training, air base performance, and Air Force laboratory infrastructure issues.

4.1 Aeronautical Ground Test Facilities

4.1.1 Introduction

It is most fitting that aeronautical ground test facilities are considered by the Air Force as a part of the New World Vistas Study. The legacy of Dr. von Karman and General Arnold has been the creation of a complex of ground test facilities that has served us well over the past 40 years, and even today represent a significant portion of our R&D and T&E testing capabilities. Although many of the technologies and flight vehicle concepts speculated in "Toward New Horizons" have been realized, they have evolved over a long period of time and, to a large extent, because the development tools were available.

Von Karman and Arnold had seen the more advanced aerodynamic and propulsion test facilities in post-war Germany and correctly deduced that their advanced technical concepts and vehicles had benefited from this test facility base.

At least three observations are significant today. First, the US major test facility base is old. Test facilities which were designed for a 25 year lifetime will soon be double this expectation. These facilities were conceived and designed in the late 1940's, but are being used to develop aeronautical concepts for the 21st century. Second, test facilities which are designed to simulate a broad range of environmental parameters have multiple usage over a long period of time (i.e., versus less expensive single-purpose test facilities). Often it is possible to extend the simulation capabilities of the single-purpose facility in a very cost effective manner to significantly enhance its usefulness for other programs and in other decades. However, when specific aeronautical development programs are funding the facilities, they are almost always designed to satisfy the minimum requirements of the sponsor. Third, major ground-based test facilities cannot be conceived and developed in parallel with the test articles that need them. A major test facility may take up to 20 years for planning, advocacy, design, construction, checkout, and operational readiness. Only then can one begin to produce the experimental information on new systems which themselves may take another 10 years to develop.

Since the days of the Wright brothers, the designers of flight vehicles have depended upon parametric evaluations and performance data derived in the wind tunnel. It is safe to say that major advances in flight vehicles are generally limited to the regime of flight simulation covered by ground test facilities. Without the relatively inexpensive data base created by the ground test facilities, flight vehicle advances have used a brute force methodology and are likely never optimized for efficiency of operation and performance. DOD studies indicate that the early phases of the airplane development cycle have a tremendous impact on life-cycle costs. For example, 65% of life-cycle costs are determined during the planning and conceptual design phase, 85% by the end of preliminary design and system integration, and 95% at the end of detail design (i.e., there is little opportunity for leverage remaining when the first airplane is

flown). One of the major influences on the design process is feedback from test articles and components in the ground test facilities.

In keeping with the spirit of the New World Vistas study, the aeronautical facilities portion only recognizes major test facility deficiencies and/or requirements. The influence of new vehicle concepts and analytical tools will be integrated into the evaluation. This should not imply to the reader that smaller and shorter lead-time environmental simulation facilities are not needed, nor should it be used to assert that types of facilities outside the technical scope of this analysis are unimportant to the Air Force and aviation industry.

4.1.2 Existing Facilities Infrastructure

With a few notable exceptions, most of the US aeronautical ground-based test facilities were constructed in the 1940's and 1950's. In keeping with the excitement of the era, there was an over-supply of some wind tunnels and propulsion developmental facilities. Every company in the aircraft business and every associated government agency had its own test facilities. (If one glances at the listing of the test facilities in the two volumes of the Aeronautical Facilities Catalogue[9], this abundance of duplicative capability is evident.) Since then there have been many closures and consolidations and some of the facilities have been upgraded. Although most of the remaining facilities do not provide the test environment of choice, they do represent much of todayís useful support infrastructure and must be maintained until replaced. These test facilities are primarily located at NASA or DOD sites, with some major test capability located at industry sites.

The continued deterioration and increasing obsolescence of the aerodynamic and air breathing propulsion test facilities calls for some actions to improve the situation:

- Budgets for facility maintenance and repair must be maintained. Major facility components are subject to failure and unexpected repairs must be handled expeditiously to prevent impact on aircraft programs.
- Facility improvement and modernization programs are essential. Older facilities can often be upgraded with new data acquisition systems and controls, providing both productivity enhancement and opportunities for new types of data.
- More attention to the aerodynamic test article and its handling can significantly enhance the usefulness of the older facilities, as well as reducing the cost of new facilities. Test models for wind tunnels can be designed safely with lower safety factors and with automated control surfaces. This permits tunnel operation at higher pressures (Reynolds number) and longer test operations without shut-down for model changes.
- Force measurements in wind tunnels can take advantage of new balance designs and more advanced calibration methods to make significant improvement in data accuracy and to reduce data differences between wind tunnels.

9. Penaranda, F. and M. Freda. 1985. Aeronautical Facilities Catalogue, Vol. I: Wind Tunnels, RP-1132. Vol 2: Airbreath ing Propulsion and Flight Simulators, RP-1133. Washington, DC: National Aeronautics and Space Administration.

- Aerodynamic data from wind tunnels can be enhanced by more use of propulsion simulators. This is particularly important for advanced fighter designs with imbedded engines, where hot-gas simulators are needed to assure proper viscous effects of mixing of gas streams.

Perhaps of greatest concern in today's environment of base closures and laboratory consolidations, is the inadvertent closure of a major and unique test capability. The DOD must be concerned not only with its own test facilities, but also those of NASA. On a typical Air Force aircraft development program, approximately 60 percent of the aerodynamic testing is accomplished in NASA facilities. The DOD has always depended upon NASA for low speed tunnels, dynamic tunnels, and spin tunnels. Further, DOD must rely upon other facilities to augment its single transonic tunnel to provide sufficient design data.

4.1.3 Facility Status and Needs

The shortage of new aeronautical test capability is not caused by lack of recognition of need or by lack of study by well informed sources. In 1988, an assessment of aeronautical wind tunnel facilities was conducted by a committee of the National Research Counci[10]. During portions of 1992, 1993, and 1994, NASA, DOD, National Science Foundation, and the Departments of Energy, Transportation, and Commerce participated in an interagency National Facilities Study (NFS)[11]. During 1993, the NASA asked the Aeronautics and Space Engineering Board (ASEB) to review the NFS report[12]. This countryís most knowledgeable experts participated in these studies and reviews.

While the 1993/94 studies adequately recognized shortcomings in present test facilities, they failed to fully represent Air Force developmental needs. This failure is attributed to two primary causes; the wind tunnel needs were primarily driven by private industry whose major interest was commercial transports and there was an apparent reluctance on the part of DOD to formally acknowledge test facility needs, most likely to avoid having to fund new test facility construction. The NSF review pointed out those deficiencies. However, the ongoing National Facilities Program, headed by NASA and driven by an industry consortium, has not fully recognized the DOD testing needs and, the DOD remains mute on the subject.

The primary aerodynamic test facilities constructed in the 1940's and 1950's emphasized simulation of compressibility effects for subsonic through supersonic flows, somewhat neglecting simulation of Reynolds number. This has caused a strong need for improved Reynolds number in future facilities as viscous flow effects and tunnel-to-flight scaling assumes a more important role in testing.

10. Review of Aeronautical Wind Tunnel Facilities; Committee on Assessment of National Aeronautical Wind Tunnel Facilities, Aeronautics and Space Engineering Board, National Research Council. National Academy Press, Washing ton, DC, 1988.

11. Assessing the National Plan for Aeronautical Ground Test Facilities; ASEB, National Research Council. National Acad emy Press, Washington, DC, 1994.

12. National Facilities Study, 1994. Volume 2: Task Group on Aeronautical Research and Development Facilities Report. April 29, 1994.

Low Speed/Transonic Wind Tunnels

The two new test facilities being pursued by the NASA Wind Tunnel Program Office are high Reynolds number facilities with high productivity—low speed and transonic. These two facilities are intended to provide the required increases in test capability and to replace aging facilities in the infrastructure. The proposed facility performance improvements in Reynolds number, flow quality, and data acquisition will permit investigation of some of the aerodynamic performance advancements stated and implied in other parts of this report. The facilities' Reynolds number limits specified to satisfy industry needs may be adequate for evolutionary aircraft developments typical of commercial aircraft, wherein few aerodynamic configuration changes are made in each generation and surprises are rare. However, military aircraft can and do change configuration radically to provide both aerodynamic improvements and to satisfy other military constraints. It is unlikely that the proposed facilities' performances provide the testing environment to sufficiently minimize development risk for advanced military aircraft.

Supersonic Wind Tunnels

The primary users of supersonic aerodynamic test facilities have been the DOD and NASA High Speed Research Program. The finding in the NFS investigation is that US supersonic wind tunnels adequately satisfy most current and potential test requirements. Shortfalls exist in productivity, reliability, maintainability, and laminar flow test capabilities. Research to define test requirements and to develop practical facility concepts for supersonic laminar flow technology is required prior to major facility modification or construction. The cost-effective development of long endurance and aerodynamically efficient supersonic aircraft are highly dependent upon the ability to construct a test facility with levels of turbulence low enough to permit the required laminar flow testing. In the meantime, upgrades and component replacements in the existing major supersonic wind tunnels are absolute needs for continued test operations.

Subsonic/Supersonic Propulsion Facilities

Many of the proposed technology advancements and vehicle concepts proposed herein place stringent demands on military engines. Requirements for global reach, absence of refueling in flight, hover, VTOL, maneuverability and large power "bleed" are in some combination coupled with such drivers as low observables (radar and infrared), lower initial and life-cycle cost, improved fuels for energy content and heat sink, long time between overhaul, and others. The development of propulsion systems which permit satisfaction of these goals is highly dependent upon the availability of ground test facilities which fully simulate the flight environment. The many engine variables that must be optimized to satisfy the diverse performance, operability, reliability, and maintainability demands can only be achieved by way of extensive experimentation and trade-off evaluations. Many thousands of hours in test facilities are required for engine development, and accelerated mission testing can be equally demanding. Although accelerated mission testing is presently conducted in static sea-level test stands, some of today's engine problems attest to a need for more complete environmental simulation of the mission profiles and engine usage.

The only major aeronautics facility construction by DOD since the early 1950's has been the Aeropropulsion Systems Test Facility (ASTF) at the Arnold Engineering Development Center. The need for this capability was recognized in the mid-1960's and planning began. Facility

design began in the early 1970's and construction began in 1977. The facility became operational in the mid-1980's, a full 20 years after the need was visualized. This facility has been available to support development of propulsion systems for the F-22 and the large high-bypass turbojets. It has been modified to permit thrust vectoring at simulated flight conditions. The ASTF gives support to the wisdom of building multi-purpose test facilities with expected long-term usefulness, for it today provides world-class capability and satisfies most of the projected engine testing needs.

The ASTF will require modifications and upgrades as new test requirements unfold. One of the major upgrades could be additional air supply and exhaust capacity to satisfy test needs of large high-bypass engines above 100,000 lbs thrust. Engine companies are already planning engines with thrust of 150,000 lbs for large commercial transports. However, the large mobility aircraft specified in this study anticipates four rather than two engines, thus making the ASTF adequate for this projected Air Force need.

Some of the Air Force missions require development of turbo-ramjets which perform over a Mach number range up to 6. A critical testing need is the transition from turbojet to ramjet mode of operation—generally between Mach numbers 2 and 4. The ASTF was initially designed to satisfy this test requirement, but will require some configuration modifications for this purpose. Other facilities are required to provide the higher Mach number test environment and they are discussed in the next section.

Hypersonic Test Facilities

Both aerodynamic and propulsion test facilities will be discussed in this section. A review of the history of hypersonic test facilities in the United States is necessary to illustrate how cyclic interests in technology and programmatic pressures can prevent rational and adequate test facility programs. Most hypersonic test facilities were built in the 1950's and 1960's to support development of ICBM's, the space program, the X-15, and the airbreathing propulsion hypersonic initiatives of that time. While a few of these facilities have survived, many were moth-balled or dismantled in the 1970's when interest in sustained hypersonic flight in the atmosphere subsided. The National Aerospace Plane (NASP) program of the 1980's had a demand for many of these same test facilities. However, no substantial test capability was possible with new construction because of the pressing and optimistic development schedule of NASP. Even efforts to bring moth-balled facilities back into operation were not timely to support NASP (e.g., the NASA Plumbrook facility). The NASP program attempted to develop in a short time several test facilities, most of which were inadequate for the needed developmental testing. Thus after a $2 billion hypersonic vehicle program, the hypersonic aerodynamic and propulsion development test community has little residual improvement to show.

Although the NRC and NFS reports address hypersonic facilities, the Hypersonic Test Investment Plan (HTIP)[13] is a more thorough review and encompasses the interests of the other studies. The need for hypersonic test facilities differs in four important ways from those facilities discussed earlier:

13. Hypersonic Test Investment Plan (HTIP); A Development Plan and Investment Strategy for US Hypersonic Test Capa bilities and Facilities. AECD-TR-94-4. Arnold Engineering Development Center, Arnold Air Force Base, Tennessee.

- There is less opportunity to acquire valid experimental data by other means (e.g., flight testing).
- The technology steps are usually steeper in hypersonics (i.e., large extrapolations from the data base).
- The environment to be simulated is usually much more hostile to the test article and the test facility, thus increasing concerns of endurance and survivability.
- It is not technically possible to construct ground-based test facilities which can duplicate the most demanding hypersonic test environments, thus forcing more reliance on a combination of testing in partial-simulation facilities and use of unproven computational codes and techniques.

The gaps between facility needs, facility availability, and facility possibilities are greatest in the hypersonic speed regime. Existing test facilities are grossly inadequate to support development of hypersonic vehicles for sustained flight within the atmosphere. While extreme hypersonic test environments cannot be duplicated in test facilities, there are techniques and technologies to permit development of hypersonic test facilities much better than those that now exist. When one couples these observations with the expressed needs for hypersonic military systems, the urgency of some needed actions is evident. Major test capability cannot be acquired without lengthy efforts for facility planning, research, design, and construction. We know that it is not possible to await the arrival of a flight system developmental program to start the facility development and acquisition process. The ground test facilities started today will determine the major developmental capability available for the first two decades of the 21st century. This available test capability will, in turn, determine the opportunities for development of hypersonic flight systems.

There are several representative hypersonic flight systems that have present or potential future interest. Space launch may be a single- or two-stage to orbit vehicle with air breathing engines and rocket augmentation. Aircraft systems have been studied which vary from Mach numbers 6 to 10. Advanced Theater Air Defense Missiles (Mach 5-10) and Advanced Ballistic Interceptors (Mach 10-20) are possibilities. Missile opportunities include Hypersonic Cruise Missile (Mach 6-8), Maneuvering Reentry Vehicle (Mach 12-26), and Tactical Boost Glide Vehicle (Mach 6-10). Munitions include the Anti-Armor Kinetic Impact Projectile (Mach 4-10) and the Kinetic Impact Earth Penetrator (Mach 4-30). Space candidates include a Space Rescue Vehicle (Mach 25-30) and Planetary Probes (Mach 25-50). Also of interest is a global reach Boost-Skip-Glide Vehicle (Mach 16-18) which operates on the edge of the sensible atmosphere.

Table 4.1.1, taken from the HTIP, illustrates the facility capability required to adequately test potential hypersonic systems. It is noted that both the required simulation parameters and the required duration of test vary for different types of testing. Figure 4.1.1 shows the adequacy of existing test facilities to satisfy the required facility capabilities.

Finally from HTIP are some hypersonic facility possibilities that satisfy some of the needs (Table 4.1.2). Low risk facilities have the technology and facility design knowledge available for immediate go-ahead. Further, good cost and performance estimates should be possible. Medium risk facilities require further development in concept and technology before facility design and construction. These facilities are thought to be reasonable extrapolations of existing

Table 4.1.1 Facility Capability Required to Adequately Test Emerging Hypersonic Systems

Type of Test	Critical Phenomena	Test Parameter		Test Time
		Duplicate	Relax	
Aerodynamic/ Aero-Optics				
Perfect Gas	Boundary Layer Transition Turbulence Flow Separation	Mach Reynolds No.	Temperature Velocity	Milliseconds
Real Gas	Chemically Reacting Flows	Gas Composition Velocity Temperature Density Scale	Run Time Density or Scale for Binary Reactions	Milliseconds
Aerothermal	Heating Rates and Aero-Shear Ablation	Total Temperature Surface Pressure Size	Mach No. for Stagnation Point Heating	Seconds-Minutes
Aeropropulsion	Chemical Reaction, Mixing, Boundary Layers & Shocks Full-size Hardware	Gas Composition Pressure Temperature Velocity Size		Milliseconds
Structure & Materials	Combined Loads (Mechanical, Thermal, Acoustics) Temperature Gradients	Gas Composition Pressure Velocity Geometry		Milliseconds

facilities. The high risk facilities require some break-throughs in test facility technologies, but the pay-off is substantial if such technical advancements can be achieved. This listing is not meant to be inclusive, and other concepts such as the ram accelerator deserve attention.

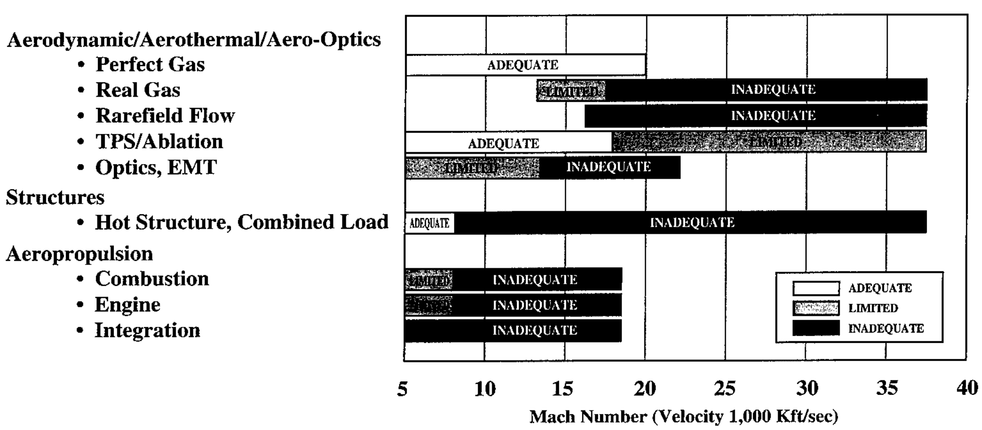


Figure 4.1.1 Summary of Flow Facility Adequacy

A new hypersonic vehicle concept may be evolving which both provides testing challenges and offers new opportunities for simulating the flight environment on the ground. It involves the projection of laser or microwave energy in front of the flight vehicle to influence the oncoming flow and produce a more favorable flow field. Those who plan new test facilities should follow such vehicle development technologies closely to assure compatibility with ground test facility concepts.

Table 4.1.2 Test Facility Possibilities

Low Risk High Energy Expansion Tube/Tunnel Mach 3-8 Clean Air Facility Structure/Airframe Test Facility
Medium Risk High Energy PGU/Multi-shock Facility Arc Heater with $P_{T2} > 200$ atm
High Risk Large, Fast Ballistic Range High Pressure Liquid Air Arc Direct Energy Addition to Gas Stream

4.1.4 Integrated Test And Evaluation (IT&E)

About 20 years ago there were those who predicted that the high speed computers and computational fluid dynamic (CFD) models would soon eliminate the need for wind tunnel testing in the aircraft development process. While both computer speed and memory as well as CFD models have advanced beyond expectations, these predictions have not been fulfilled because the early visionaries did not recognize the opportunities for synergy between the empirical and computational information. Modeling and simulation is now positioned to take even larger steps to create knowledge for decision making and risk management.

It is proposed that the T&E infrastructure be tied together to use both digital and analog simulation of subsystems under development to simulate an integrated flight system during the design phase. The Arnold Engineering Development Center is already successfully using this concept to provide early design confirmation and cost savings for weapon/stores release from aircraft. NASA Ames Research Center will use a combination of computational and wind tunnel data from several sources to provide integrated developmental information through its Inte

gration of Numerical and Experimental Wind Tunnel (I of NEWT) program. By a systems engineering approach, one can find the synergistic combination of computer modeling, ground test, and flight test that requires minimum time and cost to perform a simulation of the system. An analogy to the proposed concept is the Defense Interactive Simulation network which is used for wargaming and training.

The proposed approach also permits earlier integration of the major subsystems of the aircraft, resulting in development of a flight system which has fewer surprises and minimum need for resolution of integration issues during flight. The opportunity to bring together and integrate computational data and various sources of test data in early T&E planning will be a major contributor to the lean development initiative and a coordinated DT&E/OT&E program.

It is also proposed that the T&E community take an active role during the entire life cycle of a system, maintaining models and updating its informational data base as the flight system updates and as operational information is collected. Not only will the information be correlated and preserved, but there is an unprecedented opportunity to provide feedback to the ground test and modeling community to improve their techniques to better simulate the actual flight conditions. In the long run, this can permit more reliability to be placed on modeling and ground test results to reduce development costs, and also permit avoidance of costs associated with fixing problems that could be discovered during ground testing.

In the popular wording of today, this is a knowledge-based approach to an acquisition paradigm shift and involves development of a virtual T&E environment which uses informational technologies.

4.1.5 Summary

- With a few exceptions, aeronautical ground testing facilities in the United States have failed to keep pace with the need of aircraft and missile developments. In some technical areas, the aeronautical ground testing facilities in the US are inferior to those available in foreign, competing countries.
- During the design of modern blended wing-body airframes with highly integrated propulsion systems, many important aerodynamic design characteristics can only be properly evaluated in modern high Reynolds number wind tunnels.
- About 85 percent of an aircraft's life cycle costs are determined by the completion of its preliminary design, which requires an input of accurate aerodynamic data.
- There is an opportunity to markedly improve the usefulness of existing and future aerodynamic test facilities with relatively small costs (e.g., improvements in balances and calibration, wind tunnel models, data acquisition, and other associated test hardware).
- The length of time to advocate, design, construct and check-out modern test facilities exceeds the time required for conceptual and preliminary design of an airplane by many years. Thus, it is crucial that planning for future ground testing facilities be started early — perhaps as early as the time allotted to development of one generation of aircraft — in order to insure that the facilities are available when needed.

- Computational fluid dynamics and ground testing complement each other and both disciplines must be used in concert for the design of a modern aircraft. Potential for improvement exists in the "Integrated Test and Evaluation" concept.

In view of the above comments:

- The Air Force should make the necessary investments in the well-identified, long-range, and multiple-use testing facilities to insure their availability when specific needs arise.
- The Air Force should cooperate with NASA and industry to insure the continued availability of sufficient existing test facilities to meet near-term Air Force development needs.
- A present opportunity exists for the Air Force to eliminate a primary test facility deficiency in low speed and transonic high Reynolds number facilities. The Air Force and DOD should cooperate with ongoing NASA and industry initiatives by funding its share of facility costs and insuring that proposed facility performance is consistent with future Air Force needs.
- An investment in hypersonic test facility technology and construction must precede any future effort to develop hypersonic air-breathing propulsion vehicles.
- The Air Force should support NASA and industry initiatives to improve test techniques and test support hardware through its test centers and research laboratories.

4.2 Flight Test

Validation of flight vehicles and their systems ultimately must occur in the air. The performance characteristics of much of the flight system cannot be adequately validated or, in some cases, developed through ground testing or analytical methods. Thus, testing in flight is required to open the flight envelope for many complex flight systems. This is true now and will no doubt remain the case for a long time into the future. For example, the boundaries of safe operation for flutter, weapons carriage, and separation as well as stability and control limits for the vehicle and its systems require flight exploration and validation.

Flight testing covers a large range of applications from production acceptance flights of new aircraft to developmental flight tests to evaluate new or modified systems on existing test beds on production aircraft, to flight tests to serve as a source for invention of new ideas and concepts. The ability to continue to do flight testing at all levels must be a priority for the Air Force. The facilities at Edwards Air Force Base are a requirement. It is perhaps even more important for the future to provide opportunity to validate new concepts and to perform exploratory flight tests.

4.2.1 Prototype Aircraft

Aircraft prototypes provide the opportunity to evaluate new concepts and new aircraft systems before actually entering into an EM&D program. Fly-offs between opposing concepts can be achieved through prototyping (i.e., YF-16/YF-17 fly-off), or prototyping can provide the basis for production aircraft development as in the case of HAVE BLUE and the YF-22.

It is expected that modeling and simulation will provide for the future a scenario for actual fly-off of competing concepts in an electronic battle simulation. For complex, high performance vehicles, flight data will be required to validate the models used in the virtual battlefield simulations. The prototype aircraft can provide those data bases for simulation and provide hardware for operational evaluation as well as performance evaluation within the Air Force.

4.2.2 Experimental Aircraft

Experimental aircraft provide the opportunity to validate and explore new concepts that push the boundaries of technology and reduce the risk for transitioning technology into practical systems. Examples are the X-15, X-31, and X-29. NASA has historically pioneered the effort in evolving experimental aircraft with help, as appropriate, from DOD. In the austere times ahead, it is expected that the nation must combine efforts in a team approach to make use of its resources in developing experimental aircraft. The Air Force should play a large part in evolving and exploring advanced concepts through X-aircraft programs in cooperation with NASA, Navy, and Marines, as appropriate.

4.2.3 Flight Experimentation

Certain phenomena important to developing new aerodynamic technologies can only be explored in flight. Developments of techniques to reduce the uncertainty of Reynolds number scaling in the design process is now possible, but will need accurate flight measurement for quantification of the uncertainties of both current and new methods (Section 4.1.4). Improving the ability to predict flows which cannot be well simulated on the ground such as high-temperature, real-gas hypersonic flows, or providing boundary-layer transition data unaffected by wind tunnel noise requires flight experiments. Initial concept tests of new flow control technologies will also require flight experimentation. These experiments can often be carried out on platform aircraft, but the experiment itself is often quite complex. These flight experiments must often be designed to measure detailed flow features both on- and off-body. The Air Force and NASA have often cooperated on such flight experiments in the past, and future cooperation in this area is warranted.

4.2.4 Core Competencies

In an austere future where science and technology budgets appear very restricted, it is important that the US Air Force maintains its competency, critical skills, and resources necessary for flight testing. Prototype and experimental aircraft programs provide a means for the Air Force to remain sharp and to keep the industry capable in the design and testing of aircraft. There is a great concern that the design capability within the United States industry is deteriorating rapidly. Experimental and prototype aircraft programs are one way to retain the design competency of the nation while exploring new concepts and ideas, and reducing risk for systems that the Air Force will need in the future.

4.3 Training

4.3.1 Introduction

Advanced personnel training and selection methodologies which take advantage of new technologies to leverage future operational concepts must be developed to improve combat performance and reduce cost. The goal of the training system should be to select and train extraordinary people to do extraordinary things.

The scope of this subject includes that which is obvious and traditional; i.e., training of aircrews, maintenance crews, and C4I network personnel. The training of the industry personnel needed to design and manufacture new systems is also discussed here since it is critical to reduce costs in system development and production. It is included here due to the need throughout the aerospace industry to ensure continuous improvement in processes. There is also a need to change the usual "learning curves" that raise the cost of initial production articles. The objective is to design, fabricate, and assemble the first article (e.g., T-1) as efficiently as possible. Future low rate, "lean production" requires that added cost in learning on-the-job be reduced through training.

The Air Force should work with universities and the DOD educational infrastructure to develop a rapid feedback, continuously improving national system of education and training. The measure of success is the speed and effectiveness of training throughout the aerospace manufacturing and operational infrastructure.

4.3.2 Operational Crew Training

The most promising technology enabler is use of distributed interactive virtual combat environments (Note: The entertainment industry leads the state-of-the art, with DOD applications far behind).

> *Premission training* must leverage recent intelligence, include all relevant players at appropriate levels of fidelity for "mission rehearsal," and include use of realistic unplanned contingencies, diversions, real-time information, and "emergencies".
>
> *Training* can be accomplished *during a mission* by using the "autopilot" to relieve workload while training for terminal/threat area functions using en route updated information and on-board "embedded training" systems. En route training should focus on updated intelligence, new targets, and other mission changes.
>
> *After a mission*, recorded data should be used to learn from unplanned and/or poorly executed mission segments as well as to reinforce well executed performance.

Maintenance crew training involves use of user friendly Technical Orders and maintenance diagnostics equipment to ensure continuously improved productivity. Increased on-board fault diagnostics and health monitoring will greatly simplify and reduce the training requirements.

4.3.3 Design and Manufacturing Personnel Training

Design and manufacturing personnel need education and training to increase their productivity, and to increase their rate of improvement of the product design and of the manufacturing processes.

4.4 Air Base Performance

The subject of combat air base performance has received a great deal of attention over the past decade. This was initially due to their increasing vulnerability to attack and later, as in the case of the Gulf War, to the increasing likelihood that they would not be prepared in advance. The USAF SAB published a watershed report on the subject entitled "Air Base Performance" in November 1987 based upon its summer study of that year.

The SAB report established several principles that relate the subject to the New World Vistas study. First, the air base is an equal partner in the triumvirate that includes personnel and aircraft in the projection of air power. Second, the era of the air base as a sanctuary is over. Third, the USAF must treat the air base as a separate institutional entity with its own needs. Fourth, there are no easy or sweeping solutions to the problems of maintaining air base performance during hostilities. Instead, there are short term and long term strategies that can gradually and continually improve the situation.

In the short term, active defenses can be strengthened and the effects of attacks reduced through dispersal, hardening, and redundancy. Moreover, improved recovery techniques can restore capabilities more quickly after attack. In the long term, the best course of action is to reduce dependency on the permanent air base.

This study recommends the development of a number of new vehicle concepts that strongly support the long term air base performance strategy. Indeed, many of them were proposed in the 1987 SAB report. These include: (1) vehicles with dramatically increased reliability, durability, flexibility, and maintainability that require proportionately fewer logistics personnel and less infrastructure; (2) vehicles that consume less fuel; (3) vehicles that can take off and land in short distances and do not require long runways; (4) autonomous vehicles that can care for themselves, especially when they are failing or damaged; (5) rapid response missiles that can be delivered from a safe haven at long range; (6) high altitude reconnaissance vehicles that can determine the intentions of the enemy and remain out of harm's way; (7) long range transports that do not require intermediate bases; and, above all, (8) uninhabited aircraft that do not even require pilots or crew at the air base. New World Vistas can evidently also make a very positive contribution to the improvement of air base performance.

4.5 Air Force Laboratory Infrastructure

In general, the AF is properly organized to address the aircraft and propulsion technologies that support the concepts identified by the New World Vistas Aircraft and Propulsion Panel. The primary AF organizations are the Flight Dynamics Directorate, Aeropropulsion and Power Directorate, and Materials Directorate of Wright Laboratory. These directorates are connected through technical associations and, in some cases, formal agreements with other relevant AF, Navy, NASA and DOD organizations. Since the AF contracts out approximately 80% of its science and technology program, Wright Lab is well connected to industry and academia.

Nevertheless, closer coordination of all the government, industry, and university community involved with aircraft and propulsion technologies could further strengthen the DOD military aeronautics program in an environment of uncertain budgets and personnel downsizing in all three of the above sectors. There are several mechanisms in place for technical coordination such as DOD Project Reliance, DOD Technical Area Plan/Technology Directions Approach Activity, etc., and the recent (July 95) initiative to identify increased collaboration between AF and NASA. These mechanisms are working well to coordinate on-going programs, but more emphasis is needed on joint up-front planning of programs.

Some specific issues that need further effort to determine their resolution:

- The growing importance of S&T as the number of development programs diminishes requires that AFMC/ST and SAF/AQT be combined into one organization reporting directly to SECAF. This office would be the Assistant Secretary of the Air Force for Science and Technology, on a level equivalent to the Assistant Secretary for Acquisition (SAF/AQ). Success of this office should be judged by transition of technology from S&T to acquisition. The four AF labs would report directly to this new office, which would have responsibility for all AF S&T resources, including laboratory personnel.
- Coordination and inter-dependency between AF and NASA needs to be institutionalized in a more formal technology coordinating panel between DOD (AF-lead for fixed wing aircraft) and the four NASA aeronautics centers (Ames, Dryden, Langley, and Lewis), each of which is essential to AF aeronautics technology development.
- The AF needs to strengthen joint technology planning and program execution with Navy, Army, ARPA, Department of Energy National Labs, and other governmental entities developing air vehicle and propulsion/power technologies.
- AF labs need to increase the interaction with industry and academia through open facility use, personnel exchanges, and joint collaborative projects.
- The AFOSR 6.1 basic research program should be jointly planned and managed with the laboratory 6.2/6.3 program. There should be an on-going personnel exchange between AFOSR and the AF labs.
- The high cost of AEDC and AFFTC testing precludes the AF laboratories from testing as much as needed to develop the technologies identified by New World Vistas.
- The AF needs a well thought-out plan for facility modernization to support New World Vistas technologies and concepts. The AF should commit the necessary resources to implement the plan (Section 4.1.2).
- Wright Lab needs to manage its downsizing plan carefully (30% reduction by 1999 from 1993 levels) in order to support the technologies and system concept evaluations outlined in the New World Vistas report. Further downsizing would

greatly jeopardize the role of the Laboratory to manage and execute the programs that support the New World Vistas recommendations. The government must retain its technical expertise in order to orchestrate the AF S&T program.

- The DOD Laboratory Quality Improvement Program (LQIP), being formulated by AFMC/ST, should be implemented as soon as possible.
- The aircraft and propulsion technology S&T program is approximately 20% to 25% of the AF total S&T budget. This percentage should not decrease in order to further the recommendations of the New World Vistas Aircraft and Propulsion Panel.

5.0 Conclusions and Recommendations

This panel envisions that the Air Force will:

- *Be more reliable, flexible, survivable, and affordable.*
- *Provide global reach and project global power independent of in-flight refueling and air base infrastructure outside the CONUS.*
- *Exploit uninhabited vehicles and modularity to increase operational capability and flexibility and reduce cost.*
- *Extend capabilities in special operations, airborne reconnaissance, and humanitarian relief.*
- *Expand the air vehicle flight regime to orbital velocities and to altitudes at the edge of the atmosphere.*
- *Integrate air vehicles into information-dominated warfare.*

Based on this vision, the following conclusions and recommendations are made:

The projection of power, whether regional or global, will be critically important to the AF for the foreseeable future. This power projection is dependent upon the quality of the USAF's air vehicle systems. Thus, investment in air vehicle technologies is critical for the continued superiority of the USAF. Technology development is especially important at the present time when new weapon system starts are not planned for a long period of time.

- *Recommend a continued strong investment in air vehicle technologies.*

Significant advances in warfighting capability have been identified through seven revolutionary system concepts. These include large long-range aircraft, uninhabited aircraft, special operations aircraft, long-endurance aircraft, modular vehicles, hypersonic vehicles, and future attack aircraft. Critical technologies necessary to support these concepts are not yet mature.

- *Recommend vigorous pursuit of the enabling technologies for these revolutionary air vehicle concepts.*

Affordability will dominate development, procurement, and operation of future weapons systems. Cost prediction is essential to the determination of affordability. The prediction of cost determination based upon rational measures of merit is a fruitful area for research. Successful introduction of new technologies requires a close coupling between cost and system capability.

- *Recommend that a research effort be established to define fundamental principles of cost determination.*
- *Recommend that all S&T projects consider the proper balance between life cycle cost and capability.*

The post cold war slowdown in the development of new air vehicle systems raises a serious concern for retention of the Nation's design capability. Further, efforts to improve the performance, capability, and/or affordability of air vehicles require innovative approaches to reduce design cycle time and simplify manufacturing processes. All can be validated only by developing and producing hardware for test and evaluation. One effective way to retain and improve the Nation's design capability is through experimental and/or prototype aircraft programs.

- *Recommend that the Air Force pursue an active experimental aircraft and flight research program.*

Much of the US aeronautics test facility base is over 40 years old, almost twice its design lifetime, and generally inadequate to provide the design information and risk reduction needed in future air vehicle development programs. Some of the facility deficiencies can be overcome with facility improvement and modernization programs. However, much of the facility base can best be updated by facility replacement, where new and highly productive facilities both provide improved test capabilities and permit closure of obsolete facilities. The facility base is grossly inadequate to develop hypersonic air vehicles, and new test facilities are required.

- *Recommend that the Air Force take timely action to define and implement a program for modernization of old facilities and construction of new test facilities that ensures the adequacy of national test facilities to support future military air vehicles.*

Appendix A

Panel Charter

The Aircraft and Propulsion Panel shall identify and recommend technologies and concepts that will favorably impact the USAF's ability to accomplish its mission in the future. The Panel will work closely with the application panel~ in order to address the technology requirements for proposed air vehicle systems. The scope of the study will include, but not be limited to:

- Airbreathing Propulsion Systems
- Power Generation/Conditioning
- Fuels
- Vehicle Management Systems
- Subsystems Electomechanical
- Thermal Management
- Aeromechanics/Aerothermodynamics
- Flight Controls
- Structural and Concepts and Materials
- Cockpit and Man Vehicle Interface
- Integration of Weapons, Sensors, and Avionics
- Low Observable Technologies

In addition, the following related activities and support functions will be considered:

- Support Systems
- Maintainability
- Condition Base Maintenance (Health Monitoring)
- Design Integration
- Development Cycle/Process
- Manufacturing Technology
- Test and Evaluation
- Infrastructure
- Environmental
- Cost Modeling
- Multi-Disciplinary Integration

The study shall also consider application of appropriate commercial technology as a cost reduction parameter along with overall affordability considerations.

Appendix B

Panel Members and Affiliations

SAB Members

Dr. Richard Bradley, Chairman
Director, Flight Sciences
Lockheed Martin Corporation

Dr. William Heiser
Professor of Aeronautics
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Dr. James Lang
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Captain Christopher Berg
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Mr. William King
Manager, Air Vehicles Technology
Office of Naval Research

Appendix C

Panel Meeting Locations and Topics

22-23 March

Wright-Patterson AFB, OH

Flight Mechanics
Fuels
Manufacturing Technology
Materials
Propulsion

20-21 April

Washington DC

Active Stealth
Complexity Theory
Cost Modeling
Hypersonic Vehicles
Massive Airlift
Microelectromechanical Systems
Mini-UAV's
Ram Accelerators
Smart Structures/Skins
Special Operations Aircraft
Stealth for All Aircraft
Tilt Rotor
Transatmospheric Vehicle
Uninhabited Aircraft
Virtual Training
VSTOL
Wing-in-Ground Effect

3-5 May

Maxwell AFB AL

Air Transportable Fighter
Aircraft Range Challenges
Hypersonic Vehicle
Long Endurance Vehicle
Metrics for Aircraft Improvement
Microelectromechanical Systems
Products of Technology Invest
Special Operations Vehicle
Supportability and Survivability

16-17 May

Washington DC

Advanced Composite Structures
Advanced Sensors
Aeroelasticity and Adaptive Wings
Alternative Transport Configurations
Cruise Missiles and UAV's
Far-Term Fighter/Attack Technologies
Fighter Tactics
Fighter Technologies
Hypersonic Vehicles
Information Technologies
Integration
Materials and Manufacturing
Multidisciplinary Design Optimization
Propulsion
Simulation
Subsonic Technologies
UAV Technologies

30-31 March

Wright-Patterson AFB, OH

Air Mobility Vehicle
Alternative Propulsion
Systems
Cost modeling
Electric Power Systems
Fuels and Lubricants
Ground Test Facilities
High Speed Civil Trans Tech
Hypersonic Vehicle
Multi-Role Tactical Aircraft
Situational Awareness
Smart Materials
Special Operations
Subsonic Propulsion
Turbine Engines
Unsteady Flow Engines
Variable Flow Ducted Rocket

Appendix D

List of Acronyms

Acronym	Definition
AEDC	Arnold Engineering Development Center
AFFTC	Air Force Flight Test Center
AI	Artificial Intelligence
AOA	Angle-of-Attack
AR	Aspect Ratio
ARPA	Advanced Research Programs Agency
ASEB	Aeronautics and Space Engineering Board
ASTF	Aeropropulsion Systems Test Facility
ASTOVL	Advanced Short Takeoff/Vertical Landing
BDA	Battle Damage Assessment
C/C	Carbon/Carbon
C^2	Command and Control
CEP	Circular Error Probable
CFD	Computational Fluid Dynamics
C_L	Lift Coefficient
CMC	Ceramic Matrix Composites
CND	Cannot Determine
CONUS	Continental United States
DIS	Distributed Interaction Simulation
DNS	Direct Numerical Simulation
DoD	Department of Defense
DT&E	Developmental Test and Evaluation
ECS	Environmental Control System
EM&D	Engineering, Manufacturing, and Development
EO	Electro-Optical
EW	Electronic Warfare
FBL	Fly-By-Light

Acronym	Definition
FBW	Fly-by-Wire
G&N	Guidance and Navigation
GPS	Global Positioning System
HALE	High Altitude, Long Endurance
HMD	Helmet-Mounted Display
HOTAS	Hands On Throttle and Stick
HTIP	Hypersonic Test Investment Plan
HUD	Head Up Display
ICBM	Intercontinental Ballistic Missile
IHPTET	Integrated High Performance Turbine Engine Technology
IPPD	Integrated Product Process Development
IR	Infra-Red
IRBM	Intermediate Range Ballistic Missile
IT&E	Integrated Test and Evaluation
JAST	Joint Advanced Strike Technology
JIT	Just-In-Time
L/D	Lift-to-Drag Ratio
LAI	Lean Aircraft Initiative
LCC	Life Cycle Costs
LEO	Low Earch Orbit
LFC	Laminar Flow Control
LIDAR	Light Detecting and Ranging
LO	Low Observable
M&S	Modeling and Simulation
MEMs	Micro-Electro-Mechanical Systems
MHE	Material Handling Equipment

Acronym	Definition
MRI	Magnetic Resonance Imagery
MRV	Maneuvering Re-Entry Vehicle
NASA	National Aeronautics and Space Adminstration
NASP	National Aero-Space Plane
NFS	National Facilities Study
NRC	National Research Council
NVG	Night Vision Goggles
O&S	Operation and Support
OT&E	Operational Test and Evaluation
PBW	Power-By-Wire
PET	Positron Emission Tomography
PIO	Pilot Induced Oscillation
R&D	Research and Development
RF	Radio Frequency
RLV	Reusable Launch Vehicle
RTIC	Real-Time Information in the Cockpit
RTO	Rejected Takeoff
SEAD	Suppression of Enemy Air Defenses
SLI	Subsystems Level Integration
SOF	Special Operations Forces
STI	Synthetic Terrain Imagery
STOL	Short Takeoff/Landing
STOVL	Short Takeoff/Vertical Landing
T&E	Test and Evaluation
T/W	Thrust-to-Weight
TAROC	Total Aircraft Related Operating Costs

Acronym	Definition
TMC	Titanium Metal Matrix Composite
TOGW	Takeoff Gross Weight
TSFC	Thrust-Specific Fuel Consumption
TSTO	Two Stage to Orbit
UAV	Unmanned Aerial Vehicles
UTA	Unmanned Tactical Aircraft
VCE	Variable Cycle Engine
VFR	Visual Flight Rules
VSTOL	Very-Short Takeoff and Landing
VTOL	Vertical Takeoff/Landing
VV&A	Verification, Validation, and Analysis